PENDRAY

MEN, MIRRORS, AND STARS

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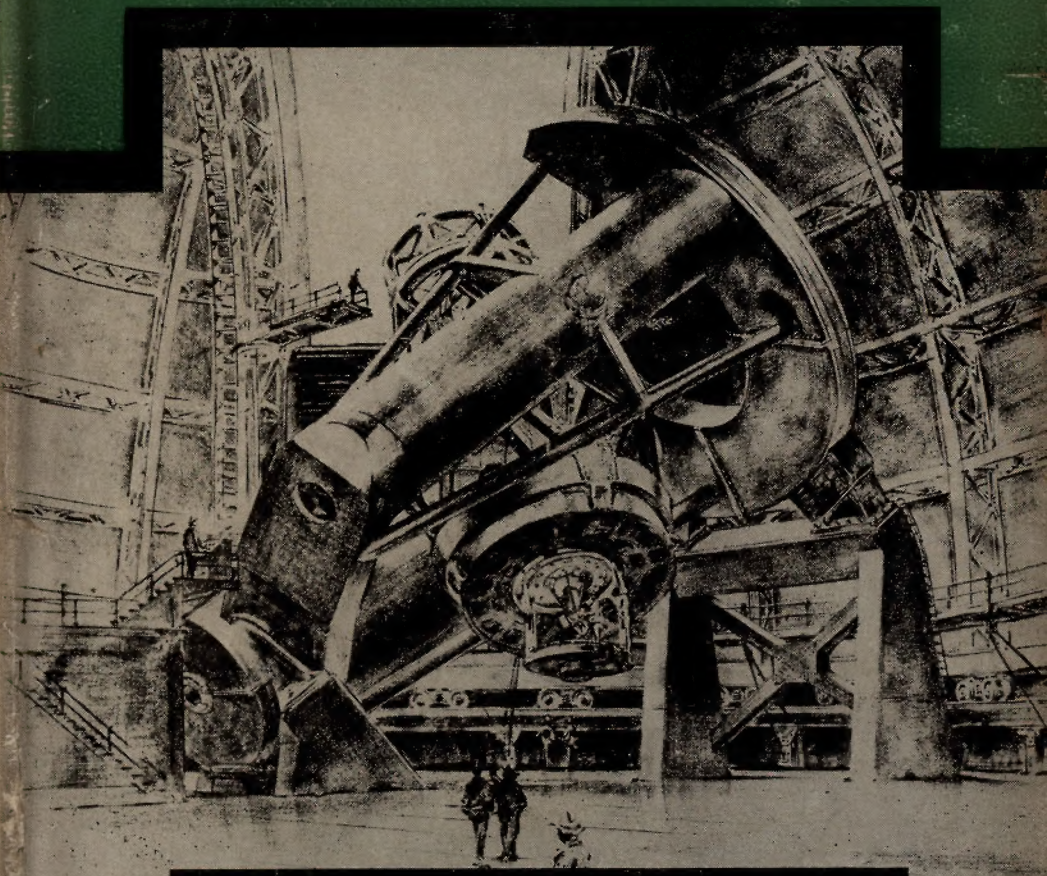
MEN, MIRRORS, AND STARS



G. EDWARD PENDRAY

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MEN, MIRRORS, AND STARS

BY G. EDWARD PENDRAY

(REVISED EDITION)

Here is an informative popular book about telescopes, the men who make them, and astronomy. This is not just a history of the telescope, the most precise and spectacular of the instruments of science, but an outline of astronomy itself, for telescopes are inextricably bound up with our rapidly unfolding theories of the cosmos.

Mr. Pendray discusses the visible universe, the progress of astronomy before the telescope, and then recounts how the first telescope came to be made and the contributions of Galileo, Keppler, and Newton.

This new and revised edition contains descriptions of all American observatories, a detailed account of the 200-inch telescope, a list of telescopes and observatory directors throughout the world and a discussion of auxiliary instruments, such as the spectroscope, the camera and the new coronagraph. There is also considerable space devoted to the place of the amateur in astronomy. The book is illustrated with interesting photographs and line drawings.

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MEN, MIRRORS,

AND STARS

ABOUT THE AUTHOR

G. Edward Pendray, whose articles on scientific and other subjects in the larger circulation magazines have given him a wide reputation, not only writes about science, but takes active part in research. Interested in astronomy, telescopes, physics, electricity, meteorology and engineering, particularly the development of rockets and jet propulsion, he has engaged in research in several of these fields. He is one of the founders of the American Rocket Society, and has been successively its secretary, president, and editor of its official publication.

Educated at the University of Wyoming and Columbia University, he was reporter and later science editor of the New York Herald Tribune, and for several years served as science editor of the *Literary Digest*. For nine years he was assistant to the president of the Westinghouse Electric Corporation, in charge of public relations and educational activities. He now serves several large industrial companies as counsel in public relations and management.

MEN, MIRRORS, AND STARS

by

G. EDWARD PENDRAY

AUTHOR OF *The Coming Age of Rocket Power*, ETC.

REVISED EDITION

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PREFACE TO THIRD EDITION

The welcome accorded *Men, Mirrors, and Stars* when it was first published in 1935, and again in 1939 when the revised second edition appeared, surpassed all expectations. Recently many readers have suggested that the book be brought up to date for a third time, for republication as soon as conditions would permit.

This volume is the result, containing as it does virtually all of the material in the previous two editions, plus a new chapter dealing with the Schmidt telescope and the Harvard coronagraph. In addition, new material is worked into several of the previous chapters, and there has been complete revision of the appendix material, including the listing, instruments and personnel of the various major observatories, which has been a continuing and useful feature of the book.

Good books about astronomy are numerous, but the telescope, chief instrumental actor in the unfolding drama of this science, has been largely overlooked by writers. There are some excellent technical treatises on the telescope, including the recent book by George Z. Dimitroff and James Baker, *Telescopes and Accessories* (Blakiston), the book by the late Dr. Louis Bell, *The Telescope* (McGraw-Hill) and the widely read volume, *Amateur Telescope Making*, edited by Albert G. Ingalls and published by the Scientific American. These books, however, are primarily for those who use telescopes or desire to construct them; they do not undertake to tell the story of the instrument for general readers.

That is the story I have tried to tell in *Men, Mirrors, and Stars*. The information upon which it is based comes from a multitude of sources. I have to thank for it many busy men

who have taken time from astronomical and other duties to explain the workings of their instruments.

I must especially give acknowledgment to the books mentioned above; to Albert G. Ingalls, Dr. Walter S. Adams and Dr. Harlow Shapley; to my wife, Mrs. Leatrice M. Pendray, who helped greatly in the original research and read and criticized the manuscript; to the authors of a score or more books on astronomy; to Dr. George Ellery Hale and especially his *Signals from the Stars* (Charles Scribner's Sons); to Professor George W. Ritchey, Alvan Clark & Sons, Warner & Swasey; Sir Howard Grubb, Parsons & Company, J. W. Fecker and other telescope-makers; to officials of observatories in America and abroad too, who freely gave information about the observatories and their work.

I wish also to thank the library of the University of North Carolina for searching out the facts about America's oldest observatory; Captain J. F. Hellweg, director of the U. S. Naval Observatory; Dr. Otto Struve, director of Yerkes Observatory; Dr. Harlan T. Stetson, former director of Perkins Observatory; Dr. Henry Norris Russell, director of Princeton Observatory; Dr. Joel Stebbins, director of Washburn Observatory and the University of Wisconsin; Alfred H. Joy, secretary of Mt. Wilson Observatory; Dr. J. S. Plaskett, director of the Dominion Astrophysical Observatory; Dr. Curvin H. Gingrich, editor of *Popular Astronomy*, and many others who graciously cleared up perplexing points, or aided in the search for historical data.

I am also much indebted to the several observatories and firms that made photographs available for the book, including Yerkes Observatory, Lick Observatory, the U. S. Naval Observatory, and Mt. Wilson Observatory.

G. Edward Pendray

January, 1946

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PART I

HOW MEN BECAME ACQUAINTED WITH THE UNIVERSE

MEN, MIRRORS, AND STARS

Chapter I

THE VISIBLE UNIVERSE, AND HOW IT COMES THAT WE KNOW SO MUCH ABOUT IT

I

IT is every man's privilege to go out of doors on a clear night, climb a hill where the horizon is wide, and gaze at the stars. Under the limitless bowl of night the quiet earth lies in a cradle of darkness. Into the distance extends the universe. Beyond the Milky Way that spans the celestial vault, beyond the faint glimmer of the distant nebula in Andromeda, still beyond the farthest visible object, the heavens open endlessly away, peopled with the countless mysterious hosts of the universe.

In these vast deeps of space the solid earth is swallowed up. The matters that have consumed us during the day fall away. Even the puny bodies which in other hours seem so vital and important are likely to be forgotten. The mind remains free to voyage through the empty spaces of the wide and kindly heavens.

To the famous American astronomer, the late Professor Simon Newcomb, this advice to look upon the night sky is usually attributed. Yet how many before Newcomb, and how many since, have sought and found solace and rest, mystery and delight in the contemplation of the heavens!

In these latter days people are not as familiar with the stars as formerly. City life is not conducive of the study of celestial things. There is too much smoke, noise and artificial light. Tall

buildings are apt to cut off the view, and the city dweller finds difficulty in locating that calm hill from which he can survey the skies.

But this need not deter anyone from following the advice of Professor Newcomb. A housetop is often as good as a hill. A small telescope can be obtained cheaply. Better yet, many Americans in the last few years have learned how to make them —small bright mirrors that can be set up anywhere; in an attic open to the skies, in backyards, vacant lots, even in the fields.

For the heavens have lost none of their fascination, whatever modern life may have added to the difficulty of viewing them. Everyone may still familiarize himself with the names and appearance of the principal constellations; may learn the locations of a few of the first magnitude stars, and know the movements of the planets and the phases of the moon.

It is true that for most of us there is no practical use to which this knowledge can be put. Yet how satisfying it is to know something about the universe of which our earth and its sun are a part, and to speculate upon our own place, no matter how insignificant, in the great drama of the galaxies!

II

The knowledge we have of the outer worlds comes to us through the agency of light. Permeating all space go the slender threads of radiation. Those beams which fall into the eye, or on the sensitive surface of a photographic plate or other apparatus, reveal their place of origin, the chemical and physical state of matter there, and sometimes the nature of the regions through which they have passed en route to earth.

But nature has been somewhat niggardly in the light-catching equipment she has supplied to us. For the perception of the gigantic and bewildering universe we have received an organ quite adequate for the ordinary purposes of life, but insignificant indeed when applied to astronomical observation.

The aperture of the eye—that is, the effective diameter of

the opening that admits light to the lens and the sensitive retina—is only one-fifth to one-third of an inch. It provides a portal for the entry of radiation equal to only about one-twentieth of a square inch, and no other light can be used except that falling in this area.

Now the sharpness of an image, and the distance at which an object can be perceived, depends directly upon the amount of light from it concentrated on the retina. An image that is too dim will not be perceived at all. One that is brighter may be seen, but no details revealed. Sharp resolution depends mainly on the brightness of the image, and in the case of distant stars this must necessarily be very little.

However, even such a minute instrument as the eye has astonishing powers. On a clear, moonless night it can see millions of billions of miles into space, provided the object seen is of enormous extent and sufficiently luminous. It can discern about 5,000 individual stars, and with the aid of proper measuring instruments—even such as the non-telescopic sextants and quadrants of the astronomer Tycho Brahe—it can determine the position of a star with an error of only about one minute of arc.

III

But when it comes to the distances, star numbers and refined measurements of modern astronomy the unaided eye clearly is inadequate.

Whereas the eye can at best perceive only about as many stars as there are persons in a good-sized theater audience, the heavens actually contain stars numbered by the millions and billions; probably many times more in our own galaxy than there are human beings on earth. It can see the planet Jupiter as a bright star, but not its nine moons, of which three are larger than our own moon. It is aware of Saturn, but the fascinating rings that encircle that planet are lost to us without other aid. The distant nebulæ, the marvelous island universes, would never have been discovered for what they are with the eye alone.

For this reason we must have recourse to an instrument that

augments the light-gathering power of the eye. This is the chief function of the telescope. In effect it enlarges the pupil of the eye to the size of its objective-lens or mirror. Since the light-catching power increases as the square area, a telescope twice the diameter of the eye provides it with four times the amount of light the eye could gather alone; a telescope of 100 times the eye's diameter increases its light ten-thousand fold.

Thus, the astronomer who looks into space with the great refracting telescope of the Yerkes Observatory does so with an eye 40 inches in diameter, catching more than 35,000 times as much light, seeing 35,000 times as clearly as with his physical eye alone. The observer who uses the great 100-inch mirror at Mt. Wilson sees 1,800,000,000,000,000,000 miles into the universe, with an eye so large he could make his bed in it. The "eye" of the observer at Mt. Palomar's 200-inch telescope could be used, if desired, for a skating rink. Its light-collecting power is 800,000 times that of the unaided eye.

IV

Yet even these huge, artificial eyes are inadequate for the complete observation and measurement of the universe.

The light by which the stars are viewed moves faster than any other thing. Upon earth it travels so quickly from one object to another, or from its source to the eye, that we naturally assume its passage to be instantaneous. Yet it is known from careful measurement that it has a definite speed, which varies somewhat according to the material through which it is passing, but which is always of extraordinary swiftness. In a vacuum like that between the stars its velocity is about 186,000 miles a second. A beam of light could therefore travel the equivalent of eight times around the earth in a single second.

For all practical purposes in daily affairs, therefore, it is instantaneous, and we can assume as much. But when the distances between various objects in the heavens are being measured, the time required for light to pass from one to the other is significant. It needs more than a second to reach us from our

closest neighbor in space, the moon. It takes eight minutes to reach us from the sun. Light travels across a radius of the solar system, from the sun to the edge of the gulf that all but swallows the planet Pluto, in about five hours. In doing so it traverses 3,800,000,000 miles of empty space—the semi-diameter of the solar system.

But these are tiny distances when compared with the magnificent emptiness that surrounds us. The sun, as a star among stars, has some close neighbors. The closest one nevertheless is so distant that light requires not minutes or hours to span the distance, but years—nearly four and a third of them. And this is the *nearest* of the visible stars, a member of the constellation of the Centaur, known to astronomers as Alpha Centauri. The next nearest, Barnard's Star, is distant more than six times as far as light can travel in a year, and hence is said to be six *light years* away, or a total of 36,000,000,000,000 miles.

Such distances of course are completely incomprehensible in terms of our experience. It is impossible, even with the aid of the familiar analogies, to provide anything more than a vague notion of them. Many stars are hundreds and even thousands of light years distant. The Milky Way itself has a diameter of about 100,000 light years—a tremendous galaxy as to size; and there are apparently no other island universes within reach of the telescope that are as large or larger. As for distance: the closest of the nebulæ outside of our own galactic system is probably the Lesser Magellanic Cloud, somewhat less than 100,000 light years away.

The most distant object visible with the unaided eye, the Great Nebula in Andromeda, is approximately 930,000 light years from us. You may perhaps see it for yourself, when the night is clear and moonless. It appears in the constellation of Andromeda, like a small, faint star, but with a certain fuzziness of outline that makes it different from the stars in its immediate neighborhood.

For all its apparent smallness, this Andromeda nebula is a giant aggregation of stars likely approaching the size of our own galaxy. The light with which we view it left the nebula

more than 9,000 centuries ago—at just about the time, as anthropologists now view it, when the ancestors of man were beginning to make their first experiments with chips of flint as tools, in an age when the mastodon and mammoth elephant were reigning monarchs of the northern hemisphere. If the Great Nebula in Andromeda had been totally extinguished at that time we would still be unaware of the disaster.

Even this monstrous island universe does not mark the end of space—does not even approach it. The great 100-inch telescope at Mt. Wilson Observatory is able to "see" into the wastelands of the sidereal universe for a distance of 300,000,000 light years. We perceive there that the cosmos is peopled with nebulæ at more or less regular intervals. The great eye of the telescope discerns them until they become mere fuzzy dots in the distance, dimmer on the photographic plate than the Andromeda Nebula to the eye.

Yet beyond them are still more nebulæ, filling out a universe so inconceivably enormous that even the astronomer is staggered by the figure of it.

Thus does the telescope lead us from mystery into still greater mystery, and there is as yet no final solution in sight. But much has been learned about the universe by means of this instrument, and much more will probably soon be learned, as we shall see.

Chapter II

ASTRONOMY'S PROGRESS BEFORE THE INVENTION OF THE TELESCOPE

I

IT would be a mistake to believe that astronomy had made no progress in the ages before the invention of the telescope, or that the astronomers of those days lacked skill in devising instruments to aid them in charting the motions of the planets and locating the exact positions of the stars.

More than two hundred years before the beginning of the Christian era, a learned Greek geographer, then head of the famous library at Alexandria, made the first attempt to measure the circumference of the earth. His methods were simple and his instruments crude, but his result, checked against the more accurate measurements of our time, was remarkably accurate.

This Greek was Eratosthenes of Alexandria, a native of Cyrene and a student of grammar, philosophy and geography. While he was pursuing these pleasant studies he was called by Ptolemy Euergetes, third of the line of Macedonians who had set themselves up to rule over Egypt, to take charge of the royal library at Alexandria, established 100 years before.

Eratosthenes was not one to content himself with executive duties alone; nor was he expected to do so. Alexandria at that time had taken the place of Athens as the world's center of culture and learning; as official librarian the Greek from Cyrene was expected to be a leader in this culture. How well he led may be seen in that triumphant feat, the measurement of the earth with the aid of a vertical peg, the shadow of the sun, and a rather inaccurate notion of the location of another city south of Alexandria.

Eratosthenes had received word that at the city of Syene, known to be approximately 5,000 stadia (500 miles) south of Alexandria, the sun at noon on the day of the summer solstice cast no shadow from vertical posts or the upright walls of houses. Moreover, the bright rays had been observed at that hour to shine clear to the bottom of the deepest wells. This would indicate, were the earth a sphere, that Syene was directly beneath the sun on the date of the summer solstice, and hence was situated at the northernmost edge of the tropical belt—on an imaginary line which we know as the Tropic of Cancer.

Reasoning that the earth is indeed a sphere, because no other hypothesis would so well fit the facts observed by travelers in many parts, the Greek of Cyrene set up a small vertical peg at Alexandria, and waited with no little impatience for the return of the summer solstice. When the great hour arrived he was on hand, armed with a bit of string and appropriate instruments for measuring angles.

We may be certain that it was a bright, clear day; else the results of that momentous experiment would not have turned out so well. At precisely the hour of noon, when the sun was highest in the heavens and farther north than it would be again for a twelvemonth, the Greek marked the end of the shadow cast from his peg. Quickly he stretched the string from the end of the shadow to the top of the peg, and measured the angle at its upper end.

This angle he found to be approximately 7 degrees and 12 minutes, or one-fiftieth part of a full circle. A simple application of the principles of geometry shows that the angle cut by the shadow of the peg is the same as the angle at the center of the earth for a segment marked off at the surface by an arc stretching from Syene to Alexandria (Fig. 1). Since this was known to be about 5,000 stadia, the distance around the earth would be fifty times as far, or 250,000 stadia.

The Greek Eratosthenes was one of the first astronomers (tho he considered himself a geographer) to realize that the value of all measurements depends on their accuracy, and that

accuracy in turn depends upon the devising and construction of instruments to aid the hand and eye. Having measured the earth once, he was not satisfied. He repeated it later, this time with the aid of an improved type of sundial, or "gnomon," which he had adapted to his needs. On the second attempt he found his results slightly at variance with the first, and enlarged the figure for the circumference of the earth over the poles to 252,000 stadia.

If the value for the stadium as used by Eratosthenes was substantially that usually ascribed, this calculation works out about 25,000 miles for the circumference of the earth—truly remarkable for an experiment carried on under such unlikely conditions, complicated by the fact that Syene was not directly on the Tropic of Cancer or exactly 5,000 stadia away. It was an application of pure geometry to the solution of a problem of early astronomy equaled only by the similarly striking tho unfortunately less successful attempt of another Greek, Aristarchus of Samos, to measure the distances of the sun and moon.

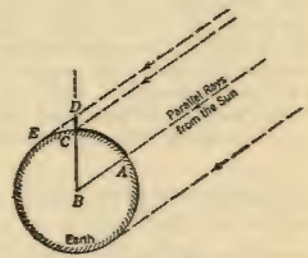


FIG. 1

How Eratosthenes Measured the Earth. The parallel rays of the sun strike the earth perpendicularly at the solstice at Syene (A) which is 5,000 stadia south of Alexandria (C). The vertical peg CD casts a shadow at E. The angle EDC is equal to the angle CBA, which cuts the arc AC. Eratosthenes found CBA to be equal to the fiftieth part of a full circle. Hence the circumference of the earth, he concluded, is fifty times 5,000, or 250,000 stadia.

II

About 270 B. C., seventy years before Eratosthenes measured the earth, Aristarchus wrote a book, fragments of which have come down to us. In it he presented a remarkable plan for measuring the relative distances of the sun and moon, by taking the angles of these bodies when the moon was exactly at the half. It is apparent that when the light of the sun on the moon, as viewed from the earth, covers half of

the lunar sphere, lines drawn from the earth to the moon to the sun will describe a right triangle (Fig. 2). If, then, an observer determines the value of the angle *MES*, at the earth, he will have two angles of a triangle, from which the third can readily be obtained. Given one of the sides—say the distance from the earth to the moon—he can then calculate the others, ascertaining not only the distance from the moon to the sun, but also the distance of the sun from the earth.

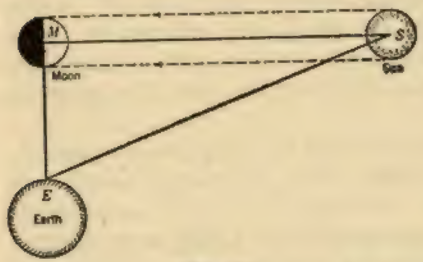


FIG. 2

Aristarchus's Plan for Measuring the Distances of the Moon and Sun. When the moon (M) is exactly at the half, the observer at E on earth measures the angle MES. The angle at the moon will necessarily be a right angle. From these two angles the third, ESM, can be calculated, and the proportional length of the three sides determined.

It was a brilliant suggestion, but unfortunately Aristarchus had no means of discovering any one of the requisite distances that would have been the key to all the others. Also, he lacked instruments of adequate precision, and was unable to measure the angles with sufficient accuracy to learn even the *relative* distances of these heavenly bodies. He determined the sun to be only twenty times as far from the earth as the moon, whereas in fact it is about 400 times.

Tho this experiment failed, the idea behind it showed the kind of ingenuity possessed by astronomers of those days, who had the temerity to try to measure the solar system by plane geometry. Aristarchus of Samos will be remembered as long as there is a history of astronomy, not only for this suggestion but also because he had what was for his day a most curious and advanced idea. It was that the earth, instead of occupying the center of the universe, is a planet, like Venus and Mars, and that in reality it is the sun that stands at the center of creation.

This was in the year 270 B. C.! His inspired guess was to remain unbelieved and almost forgotten for 1,500 years, and when rediscovered finally was to call down the wrath of authority, to cost Giordano Bruno his life at the stake, and force upon Galileo Galilei the humiliation of recantation on his knees. Even in Aristarchus's time it was a dangerous doctrine, and subjected him to abuse, attack and the threat of indictment on the ground of impiety.

III

Before Aristarchus and Eratosthenes there had been astronomers and astronomer priests in the ancient world for hundreds, perhaps thousands of years.

The earliest peoples of Europe and Asia associated the motions of the stars and planets with good and evil spirits. In later times they came to believe that the movements of the heavenly bodies controlled, or at least forecast, important human events. One of the pastimes of shepherds and tellers of folk-tales was to discern figures of humans and animals in the stars and identify them with heroes or gods. By this process many of the constellations were named long before the beginning of historical times.

Records dating from the time of the Assyrian King Sargon, father of Sennacherib, suggest that even then the skies had been watched and charted for many generations. The Chaldeans, working out their system of divination by the configurations of the heavens, discerned seven spheres, which they assumed to be revolving around the central earth—sun, moon, Mercury, Venus, Mars, Jupiter and Saturn. The seven spheres were sacred; they found their counterparts on earth in mystical combinations of seven. Thus there were seven days in the week, seven plagues, seven deadly sins; and later, seven wonders of the world, seven years of bad luck, seven-year locusts.

The seven planetary bodies soon became symbols of seven gods and goddesses of the Babylonian pantheon, and corresponding days of the week were dedicated to them. Saturday,

named for Saturn, became identified with the Jewish Sabbath; Sunday, named for the Sun, with the holy day of the Christians; Monday is the day of the Moon. The names of the other days whisper still their ancient religious origin. Tuesday is associated with Tiw, Germanic god of war, corresponding to Nergel of the Babylonians and Mars of the Romans. Wednesday derives its name from Woden, the Germanic equivalent of Jupiter; Thursday from Thor, equivalent to Mars; Friday from Frigga, the Norse version of Venus, goddess of love.

Babylonian doctrines spread throughout the ancient world. Egyptian astronomy was influenced by it, tho in that country observation of the stars and planets probably began independently. The knowledge of the Chaldeans was first carried over into Greece about the middle of the seventh century B. C. At this time a school of philosophy and astronomy was founded by a Babylonian philosopher named Berossus on the island of Cos, and from this point knowledge of Eastern science began to permeate Greece. It received great impetus when, about 100 years later, the great Pythagoras of Samos made an extended trip in the lands of Egypt and the Chaldeans. He came back with knowledge of the movements of the sun and planets. He understood that the earth is tilted at an angle to the plane in which the sun and planets appear to revolve, and had been told that we live upon a globe afloat in space.

Pythagoras had many followers, some of whom ended by assuming not only that the earth is poised in space, but also that it rotates on its axis. One of these worthies was Hycetas of Syracuse, later to be mentioned by Copernicus in his revolutionary book on the motions of the celestial orbs. Another was Heraclides of Pontus, a disciple of Plato about 360 B. C., who invented a modification of the geocentric system of the universe, suggesting that while the sun undoubtedly revolves around the earth, it in turn is the center of revolution of the planets Mercury and Venus.

These curious, almost successful gropings in the right direction were offset by the parallel development and gathering strength of another idea, also brought from the East by Pythag-

oras: that the earth is the center of the universe, and about it all stars and planets wheel.

Four hundred years before Christ a Greek philosopher, Eudoxus of Cnidus, set himself the mathematical problem of explaining how the earth could be the center of the universe and at the same time accounting for vagaries of motion of the planets which under that theory cannot help but make themselves known. He succeeded in a way that recommended itself to astronomers and theologians alike. He assumed that the sun, moon and five planets were revolving around the earth embedded in huge, perfectly transparent spheres. But instead of being set directly into the spheres each planet was mounted on a smaller sphere, which was itself mounted in the larger one. The number of different spheres needed to account for all known movements, he determined, would be twenty-seven, all rotating at different rates of speed.

Unfortunately for this excellent device, the improvement of methods of observation continually disclosed new wabbles in planetary motion. Each new wabble required the invention of a new subsphere to explain it. Almost every sage who examined the theory after Eudoxus found it necessary to add complications until, by the time of Aristotle, there were at least fifty-five different intercalated spheres. Before the idea finally came to be abandoned, in the sixteenth and seventeenth centuries, the number had reached the interesting total of seventy-seven.

IV

Other work of the ancient astronomers was more to the point. In the year 130 B. C. Hipparchus, greatest of the Greek astronomers, made the discovery of the precession of the equinoxes, a movement which we know to be due to a regular 26,000-year revolution of the poles of the earth. It speaks well for the old Greek and his instruments that it should have been discovered at all, for the amount of movement in a year, or even in a century, is relatively slight.

Hipparchus came upon it while comparing some old star

charts with his own, and he noted that the whole bowl of the heavens seemed to be shifting with relation to the earth. This movement manifests itself to observers as a slow westward progression of the imaginary point where the plane of the earth's equator cuts the line of the sun's course among the stars.

It is induced in the earth by the pulls of the sun and moon on the bulging equator, to which the earth reacts like the great gyroscope which it is. The result is a motion like that seen in rapidly spinning tops which are slightly inclined to the perpendicular. The wabble carries each pole of the earth through a circle once each 26,000 years, the north pole stars alternately being Polaris (at present) and Vega (12,000 years from now).

The discovery is more than interesting; it is of great practical importance, for the intersection of the equatorial plane and the sun's course, or rather the meridian passing through that intersection, is used by astronomers in measuring the longitudinal position, or *right ascension,* of the stars. While the annual movement is too small to be of great significance, the cumulative effect over a period of years is measurable, and corrections must be applied continually to old star charts to bring them up to date.

Hipparchus also catalogued 1,080 stars, a remarkable accomplishment for his time. The catalog was adopted almost entire by Ptolemy, his successor, and by him handed down to the Middle Ages. Its star positions, 1,500 years later, aided Columbus to discover America and Vasco da Gama to round the Cape of Good Hope. In this catalog Hipparchus divided his stars into six classes or "magnitudes," according to brightness, a device so useful that it remains a part of the system of astronomers to this day.

Finally, he invented the mathematical science of trigonometry, which treats of angles and triangles. Astronomers, looking back upon the zeal and discernment of this old Greek, have cause to thank him above all else for that. Trigonometry helped Hipparchus to solve many baffling problems raised in his day by the motions of the planets. In our time it reveals the magnitude of the farthest galaxies and permits computation of the distances and diameters of the stars.

V

If they lacked telescopes, the Ancients were by no means without instruments. Indeed, they made use of such a bewildering array of implements as to shame modern observatories, which have only a few relatively simple ones by comparison.

These devices were mainly for measuring angles, such as the cross-staff, quadrant or sextant; time-tellers and shadow-measurers like the sundial, the gnomon, the clepsydra and hour-glass, and simple aids to calculation or observation such as the armillary sphere and the astrolabe.

The simplest of astronomical observations (aside from merely distinguishing the constellations) requires some kind of aid in determining the position of the body under consideration, or measuring the apparent distance between it and a neighboring object. The sky position is most easily established by finding two coordinates: the *declination* of the body, or its distance north or south of the equator of the great celestial sphere which encloses the earth, and its longitudinal position, or *right ascension.*

Both of these require precise measurement of angles, and the unaided eye is not well adapted to making decisions of this kind. For instance, ask a dozen persons at random to state the apparent diameter of the moon. The estimates will vary all the way from half an inch to the size of a pumpkin. The fact is that a disc the size of a pea, held at arm's length, will cover the face of the full moon very nicely.

The problem becomes even more difficult when a fairly large or a quite small angle is involved—for example, the angular distance of the moon above the horizon when it is two hours high, or the small angular separation of the star Mizar (at the bend of the handle of the Big Dipper) and its faint companion Alcor.

An apparatus like the ordinary compasses or "dividers," con-

sisting of two legs hinged together at one end and provided with a scale marked off in degrees, is the simplest kind of device for measuring angles. By applying his eye to the hinged end, and sighting along the legs, meanwhile adjusting them until they bear upon the objects being measured, the astronomer can read off the angular separation on the scale.

The quadrant and sextant, standard equipment for astronomers and navigators before the day of telescopes, were based on this principle. In the most common form they consisted of frames representing a segment of a circle (in the case of the quadrant, a quarter circle; the sextant, a sixth of a circle) and provided with a movable arm sometimes equipped with sights. Larger and more elaborate quadrants were trued with a plumb-line, and had degree circles of brass or other metal divided as finely as the maker could manage.

A variant of this idea was the cross-staff, favored by mariners because of its convenience. It was a necessary part of the equipment of navigators even into the fifteenth century. Columbus used a cross-staff on his voyage to the New World, together with an astrolabe. It was a contrivance made of two wooden rods, one perhaps a yard in length, the other shorter. The longer stick was provided with a sight at each end, and the shorter with only one. The latter was affixed to the long staff on a sliding joint that permitted it to be moved easily back and forth, but maintained the angle between the sticks always at 90 degrees.

To obtain the elevation of the sun or a star, the navigator held the instrument so that the longer stick was horizontal, the shorter vertical. Applying his eye to the near end, he sighted the horizon with the long stick, and the object to be viewed through the sight at the upper end of the short stick. Moving the vertical member back and forth until the object could be seen plainly through the sights, he then read the angle from a calibrated scale on the long member.

Another form of the cross-staff, better balanced, was widely used in astronomical work and navigation (Fig. 3). In this instrument the cross member was gripped by the slide-joint at the

exact center, and was supplied with sights at each end. To find the angle subtended by two stars, or the elevation of a body above the horizon or other point of reference, the observer applied his eye to the one sight on the long member, and brought the two objects into view through the sights at either end of the cross-stick. The angle was read as before from a graduated scale along the main member, or it could be worked out by plane geometry, the figure making a double right triangle with two sides and one angle known.

An instrument similar in principle, but of greater refinement, was the *astrolabe* (Plate 2). Its invention is usually attributed to Hipparchus or to Apollonius of Perga, a predecessor of Hipparchus who lived about 240 B. C. It bears evidence, however, of an ancient and distinguished ancestry. In its simplest form it consisted of a disc of wood or metal inscribed around the circumference with degrees for measuring the altitudes of stars or the sun. Pivoted at the center was a sighted diametrical pointer or *alidade,* which owes its modern name to the Arabian astronomers.

To this simple arrangement Hipparchus added his *planisphere* —a circular map of the stars as they would appear if projected upon a plane lying perpendicular to one of the poles of the earth. In later times this planispheric star chart was called the *rete,* and was superimposed on the original circular disc of the instrument, often with named pointers to locate the positions of the brighter stars. The instrument also often included a zodiac circle, showing the sun's position for every day in the year, and such additional items as the fancy of the maker could suggest.

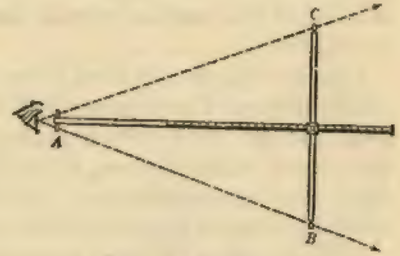


FIG. 3

The Cross-staff. The astronomer sighted along AB and AC to two bodies under observation, moving the cross-member along until properly adjusted. He then read the angle from the scale.

The result was an instrument almost as mysterious to the uninitiated as the modern engineer's slide-rule. But in the hands of a skilled navigator it could be used to tell the time, obtain latitude, aid in calculating distance traveled by dead reckoning, and in working out a great variety of problems.

Finding the time, for example, was accomplished in this manner: First the mariner measured the altitude of the sun by holding the astrolabe by its handle and sighting along the movable alidade. Then he consulted the zodiac circle for the sun's position for the day and adjusted the rete accordingly by rotating it until a marker for the sun's position corresponded with the observed altitude. Since this in effect brought the planispheric projection of the heavens into coordination with the actual situation of the stars at the moment, the navigator had in his hands a convenient analog of the sky, and the time could be deduced either by calculation or by reading it from a scale of hours ranged around the circular scale of degrees on his instrument.

Of the several ancient devices for telling time or obtaining the altitude of the sun by means of shadows, the *gnomon* was the simplest. Its beginnings were undoubtedly the same as those of the ordinary sundial: a simple vertical post affixed to a flat plate, the latter marked with the position of the shadow at noon of the summer solstice and a scale of hours or degrees on either side.

Simple dials of this kind were among the most ancient time-telling devices. There is mention of a sundial in the Old Testament; Isaiah 38:8, which reads: "Behold, I will bring again the shadow of the degrees, which is gone down in the sundial of Ahaz ten degrees backward. So the sun returned ten degrees, by which degrees it was gone down."

This record of a miracle—one even more remarkable than that vouchsafed Joshua—dates to about 710 B. C. No sundials of such age have survived, but there is a very old one in the Berlin Museum, an Egyptian relic of uncertain antiquity. It is curiously designed, being shaped like a horizontal capital L. On the short, vertical limb of the contrivance a cross-bar has

been affixed in such a way that its shadow is cast crosswise on the longer part, and the latter is marked off in hours by six lines.

The sundial (Plate 2) provides a measure not only of the time but also of the sun's elevation. To increase the accuracy of the instrument for astronomical use the vertical peg in Grecian times was mounted at the bottom of a hollow hemisphere of metal, the tip of the peg reaching the height of the rim. The advantage of this arrangement is that every part of the background upon which the shadow falls is equidistant from the peg tip; hence there is none of the distortion inherent in every sundial of the flat or angular type.

The inside of the hemispherical gnomon was usually inscribed with a pattern of circles centering on the base of the vertical peg, crossed by radial lines also centering on the peg. If to be used for telling time, the circles represented hours; if for astronomical work, degrees. In use the gnomon was placed on a suitable surface, with the rim of the hemisphere perfectly horizontal. Both the height and direction of the shadow could then be read off in degrees (Fig. 4).

The invention of this ingenious kind of astronomical sundial is attributed to Aristarchus of Samos. It was such a gnomon that Eratosthenes is believed to have used in refining his measurement of the circumference of the earth. In some parts of the world pocket sundials based on this same hemispherical principle are still in use today.

Eratosthenes himself is credited with the invention of the *armillæ*, or *armillary sphere*. This is a complicated-looking contrivance (Plate 2), a representation

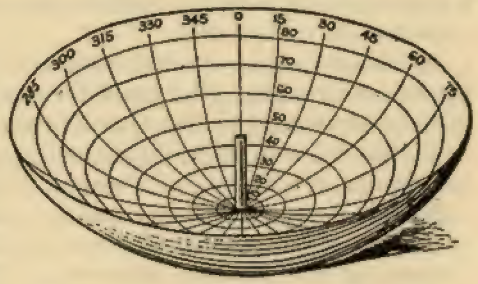


FIG. 4

Plan of an Astronomical Gnomon. The hemispherical bowl contains a vertical peg and appropriate markings.

in metal of the celestial sphere, with the earth in the center, surrounded by one or more rings representing the horizon, the equator, the zodiac, the meridian, etc. In its earliest form it probably had only one or two of these different kinds of circles, according to the kind of problem it was to help solve. Eratosthenes is said to have used a *solstitial armillæ* in his attempt to measure the tilt of the earth, or obliquity of the ecliptic. This form contained a ring fixed in the plane of the meridian, and an inner equatorial ring that could be rotated. The altitude of the sun was taken by rotating the inner ring until the shadow of its upper half exactly covered its lower half, the angle being read from a scale on the meridian ring.

An even simpler form was the *equinoctial armillæ*. It contained only one bronze ring mounted in the plane of the equator. It could be used to determine the time of the equinoxes (the time which occurs twice each year when the sun is exactly over the equator) by noting when the shadow of the upper part of the equatorial ring exactly covered the lower part.

There were many other types, some quite complicated, useful in explaining observed phenomena or in working out astronomical problems. Hipparchus used one containing four rings, representing the equator, the meridian, and the tropics of Cancer and Capricorn. Ptolemy added a further improvement: diametrically opposed tube-like sights on the meridian circle and a plumb-line to hold the instrument in proper position with respect to its vertical axis.

By Ptolemy's time (second century A. D.) various innovators had added ring after ring, until the astronomers at Alexandria in the first century of the Christian era had armillary spheres with *nine* different rings, depicting the equator, horizon, meridian, tropics of Cancer and Capricorn, the arctic and antarctic circles, the zodiac and the ecliptic. (Such an armillary sphere, of Italian workmanship, is shown in Plate 2.) To these embroiderings the Arabian astronomers, following the downfall of Alexandria, added an alidade, or sighted rule, taking the idea from Ptolemy's tubular sights. In this form they passed the instrument on to the Europe of the Middle Ages.

VI

The principles of the armilla and the quadrant were used in a number of the spectacular and astonishing pretelescopic instruments constructed in the sixteenth century by Tycho Brahe, last and greatest of the astronomers who worked with the unaided eye.

Before Tycho's time the fields of astronomy had been well gleaned by able men. After the day of Hipparchus and Ptolemy, science passed into the hands of the Arabs, who made good use of it, preserving the knowledge of the Ancients until such time as Europe should again become civilized, adding to it many improvements and embellishments. Astronomy returned to Europe through them in the twelfth and thirteenth centuries, and gradually made its way from Spain and Italy northward into the outlands of Poland, Germany and the Scandinavian countries.

For the most part the advances in astronomical knowledge from the time of Ptolemy to Tycho Brahe were philosophical rather than observational. Tycho, unlike many of his contemporaries, was interested in viewing the skies, not in theorizing about them. He was a bumptious, conceited, irascible, paradoxical man, not above practising astrology when it suited his purposes, theatrical in his methods—but above all the most careful and accurate observer in all the ages of astronomy before the telescope.

With him the ancient instruments for astronomical research reached magnitudes and a refinement never again approached. In our day we speak respectfully of telescopes 60 and 100 inches in diameter, and regard with something like awe the 200-inch telescope now being constructed for the California Institute of Technology. What, then, shall we say of the instruments of Tycho Brahe? When he was only twenty-two he constructed a quadrant so large that twenty men were required to mount it on the hill from which observations were made. The radii of the quadrant were nineteen feet long, built of seasoned oak joined by elaborate wood framework. The arc, also of oak,

carried a strip of brass divided into minutes, and the whole apparatus was enclosed in a pivoted, movable cubical framework more than twenty feet on a side. This was only a youthful attempt, but it showed the promise which was abundantly fulfilled in maturer years.

Tycho was born in 1546 at Knudstrup, in Skane, a Danish province. His family, fortunately for his ambitions, were both prominent and on friendly terms with the Danish king. He studied astronomy at Copenhagen, Leipzig, Rostock and Augsburg, and in 1571 prevailed upon his maternal uncle, Steen Bille, to construct an observatory for him at Heritsvad Abbey, near Knudstrup.

It was while working at this observatory in 1572 that he saw the great apparition that confirmed his interest in astronomy and really started him on a notable career of stellar and planetary observation. It was the appearance of a "new star," a phenomenon known in our time as a *nova*. "I was so astonished at this sight that I was not ashamed to doubt the trustworthiness of my own eyes," he wrote. "A miracle indeed, either the greatest of all that have occurred in the whole range of nature since the beginning of the world, or one certainly that is to be classed with those attested by the Holy Oracles, the staying of the sun in its course in answer to the prayers of Joshua, and the darkening of the sun's face at the time of the Crucifixion."

With feverish haste, in fear lest it should disappear before he could complete the recording of it, he set to work observing his miracle. He found it to lie in the constellation of Cassiopeia, and determined its position with the aid of a sextant he had just completed, with walnut arms five and a half feet long, three inches wide and two inches thick—certainly a sturdy if somewhat unwieldy instrument. The movable arms were held within two metal semicircles, one graduated with a scale of minutes, the other serving as a brace.

The notion of making these large and ungainly instruments first came to him when he was seventeen. He was then using a pair of ordinary compasses, by holding the center near his eye and pointing the legs at the objects in the sky. The manifest

inaccuracy of this crude device stirred his curious passion for solving a problem, and set him to thinking how instruments might be constructed to reduce the margin of error in astronomical work, which he knew to be greater than 10 minutes of arc, or nearly a third of the apparent diameter of the moon, even in the best observations of the Greeks.

Tycho perceived that one way to improve his readings would be to construct instruments of greater size, especially sextants and quadrants.

The advantage of size is in the greater number of segments into which the enlarged scale can be marked off. There are 90 degrees, or 5,400 minutes, in a quadrant. But a minute of arc is still a large angle for astronomical purposes, representing as it does about a thirtieth of the apparent diameter of the moon. The exact astronomer desires to refine his measurements to seconds and fractions of seconds; yet on the scale of a quadrant there will be sixty seconds to each minute, or a total of 324,000! To provide second marks one-sixteenth of an inch apart (the smallest divisions by which an ordinary inch rule is marked) the scale of a quadrant would have to be about 1,700 feet long, or nearly a third of a mile, the movable arms in proportion.

If such huge contrivances had been practical, Tycho probably would have built them. He did the next best thing; he devised instruments as large as possible, and then sought ways of marking the scales in as many equidistant divisions as could be achieved without sacrificing accuracy and legibility.

One method, often used, was to mark the minutes

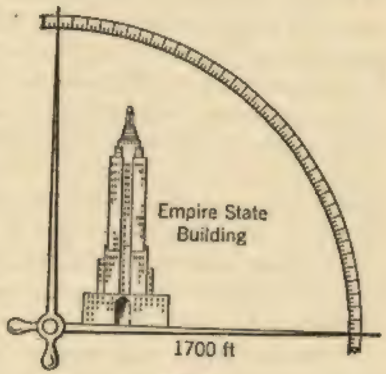


FIG. 5

A quadrant would need to be about 1,700 feet tall to provide an arc on which second marks could be placed one-sixteenth of an inch apart.

with long lines extending toward the pivot of the instrument or the center of radius of the circular scale. Between these minute marks were then placed subdivisions along an angular line extending from the lower end of one minute mark to the upper end of the next (Fig. 6). This method permitted the subdivisions to be placed a measurable distance apart on the diagonal, yet brought their intervals to such a small size, as measured in the radial direction of the instrument, as quite appreciably to increase the accuracy of the readings. The diagonal rows of minute subdivisions were known as *transversals.*

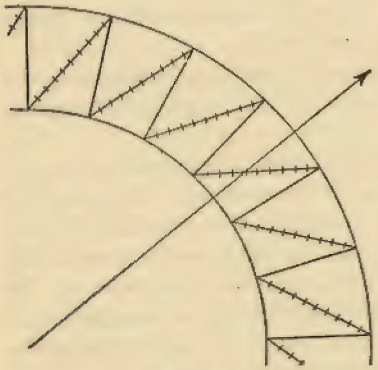


FIG. 6
One method of marking a scale into fine divisions with "transversals."

By such devices Tycho was able to increase the accuracy of his observations many times over the best of his contemporaries, and far exceeding that of the finest measurements of Hipparchus and Ptolemy. Supplementing his large instruments and his transversals, he hit upon the happy device of averaging the errors—a process of striking a mean value for many observations made by the same and different instruments, thus statistically reducing the variation. With the aid of his instruments, Tycho improved upon the accuracy of the Greeks by a very considerable amount, reducing the probable error between two neighboring stars from 10 minutes of arc to about 57 seconds (from a third to a thirty-first part of the apparent diameter of the moon).

If these results still appear grossly inaccurate when compared with the thousandths of a second allowable in modern work, it must be remembered that they were achieved without the aid of any magnification whatsoever, and depended only on his instruments and the sharpness of Tycho's good eyes.

VII

The triumph of Tycho's career was the construction in 1576 of the observatory *Uraniborg* ("fortress of the heavens") on the island of Hveen in the Baltic Sea not far from Copenhagen. It was made possible through a magnificent grant of funds and land from King Frederick II, of Denmark. There Tycho gathered the greatest collection of giant instruments that ever saw the light of day; bringing in several that he had made before, and relics he had gathered in his travels, but for the most part constructing them in the shops of Uraniborg, which in this respect was like well-equipped observatories of today.

One of the special marvels of the place was the huge *mural quadrant* mounted on the west wall of the main observatory. It consisted of a circular scale of degrees placed against the wall —marked on a strip of brass five inches broad, two inches thick and six and three-quarters feet in radius. In the center of the arc, in the south wall, there was a hole into which a cylinder and pierced circle of brass had been placed, and through which observers could sight along the sliding bars of the quadrant.

The usefulness of this elaborate mechanism may be somewhat dubious, but not its beauty. The curious imagination of Tycho caused him to adorn it, and the wall surrounding it, with elaborate, highly colored decorations and murals depicting himself and many of his other instruments, of which he was inordinately proud (Plate 3).

The castle contained not one observatory, but several. In its southern wing a second station was fitted out with a vertical semicircle eight feet in diameter, turning upon a vertical axis and furnished with a horizontal circle for measuring azimuth, or direction right and left along the arc of the horizon. Supplementary equipment included a *triquetrum,* a medieval instrument having three graduated sides, used in measuring angles somewhat as a protractor is used by modern draughtsmen; a six-foot sextant for measuring altitudes, and a smaller one of only two-foot radius but equipped with an azimuth circle.

An observatory in the northern wing contained another triquetrum, mounted in such a way that it could be used with an azimuth circle sixteen feet in diameter resting on top of the tower; a sextant with four-foot arms; a double arc, and an important historical relic, a triquetrum made and used by Copernicus, whose work Tycho admired greatly, but whose theory of the planetary system he rejected as impossible. This interesting object shows that Copernicus, tho a philosopher and mathematician rather than an observational astronomer, was an instrument-maker of the first rank. His triquetrum was eight feet long, fashioned of pine and divided by ink marks. The two short equal arms forming the legs of the triangle were each divided into 1,000 parts; the longer arm into 1,414.

The castle Uraniborg housed a number of smaller observatories in addition to those enumerated. When he wished, Tycho could have all the parts of the heavens surveyed at once by his assistants. Each of the smaller observatories contained, as permanent equipment, an equatorial armillary sphere like those of the Alexandrine Greeks, only larger and more complicated, and ornamented with pictures of Copernicus and Tycho.

Supplementing the main stations, Tycho in 1584 built another large observatory outside of Uraniborg, but on the same island. It was entirely underground except the roofs. By thus burying his instruments below the surface of the earth the astronomer sought to avoid vibrations caused by wind and noise.

The underground observatory was laid out in a manner to make simultaneous observations possible with several different kinds of instruments, and yet to isolate the assistants making the observations so that they could not compare readings with each other. To this end the observatory consisted of five rooms communicating with a central study.

The major work of observations was carried on in the crypts, in the center of each of which was a large instrument. One contained an azimuthal quadrant five and a half feet in radius, and an azimuth circle at the top of the wall. Another held a zodiacal armillary sphere; a third contained a large quadrant of brass seven feet in radius, enclosed in a square of steel and likewise furnished with an azimuth circle on the wall; a fourth, a sextant with arms five and a half feet long for measuring distances, and the southernmost and largest crypt contained an instrument of interesting design, consisting of a declination circle nine and a half feet in diameter, revolving around a *polar axis,* and a semicircle twelve feet in diameter, supported on stone piers, representing the portion of the celestial equator visible above the horizon.

This instrument is of especial interest to historians because it indicates that Tycho had discovered the polar axis, now widely used with large equatorially mounted telescopes. It is an axis lying north and south, and tilted up at its northern end until it is parallel with the true axis of the earth. The angle of its elevation depends, of course, on the latitude of the observatory. An instrument turning on a polar axis can follow a star across the heavens with no other adjustment except that of rotation; whereas any other type of mount, such as the altazimuth (permitting motion both in altitude and along the horizon) must be continually adjusted along two axes to follow the apparently curved motion of a star. It was a type of mounting that Tycho undoubtedly found convenient; for modern photographic telescopes it is an absolute necessity.

Tycho's instruments and his personality were of such spectacular nature as to overshadow to a large extent the really fine and important contributions he made to the science of astronomy. We have already seen how he succeeded in improving the accuracy of measurements and how he discovered a nova. These were no small achivements for his day; they represent the final gleanings in a field that had already been thoroughly searched by his predecessors. Since, with all the cleverness he used in fashioning instruments, Tycho knew no method by which the light-capacity of his eyes could be increased, he had to be content to measure more closely than ever before what was contained in the constricted universe visible to him.

Fate cheated Tycho Brahe. He died in 1601—missing by only seven years the advent of that most marvelous of all astronomical instruments, the telescope.

Chapter III

HOW THE FIRST TELESCOPES CAME TO BE MADE, AND WHAT FOLLOWED

I

THE story of the telescope begins quietly, in the humble shop of an obscure spectacle-maker of Middelburg, in Zeeland, a province in the southwest part of the Netherlands.

The exact date of the discovery that was to make this spectacle-maker immortal is not known, and the circumstances of it are buried in legend and conjecture. As the story goes, the optician, Jan Lippershey by name, held up two lenses in his hands one bright day and looked through them toward the steeple of a nearby church. By accident these lenses were respectively convex and concave, the latter nearest the eye. To the great astonishment of the spectacle-maker, they brought the distant steeple almost within his shop, so that he was able to view the object as if, indeed, it were only a few feet away.

There was only one thing for him to do then. He grasped at once the enormous value of an instrument that could bring distant objects close, and saw especially the usefulness of it in time of war; a natural connection in the Netherlands, which in the early part of the seventeenth century was plagued with war and rebellion.

He immediately communicated with the ruling body of the country, the States-General, asking for a thirty-year patent giving him exclusive right for that period to manufacture these instruments. As an alternative, he proposed that in return for a suitable pension he would make "instruments for seeing at a distance" exclusively for his country's service, and keep the

secret from all persons who might let it fall into the hands of an enemy.

His application for a patent was received on October 2, 1608, and if Lippershey was quick to see the possible usefulness of the instrument, the States-General was even quicker. It immediately appointed a committee to test Lippershey's telescope from a high tower of the palace of Prince Maurice, and appropriated 900 florins to pay for it should the instrument prove as serviceable as the inventor claimed. The members of this committee severally gazed through it and were amazed and delighted. Four days after applying for a patent Lippershey had made a sale. The committee reported favorably.

The assembly thereupon agreed to pay for the telescope, but some of the gentlemen thought it would be more convenient if arranged for both eyes instead of one. Lippershey was forthwith commanded to devise such an instrument, and within two months completed it, thus becoming within the space of a few weeks the inventor not only of the telescope but also of the binocular.

Jan Lippershey did not receive his patent, however. His application had hardly been made a matter of public record before a great clamor was raised by persons who asserted that they, and not Lippershey, had been first to make such an instrument. One of the most persistent of the claimants was Jacob Adriansz, surnamed Metius and a brother of the mathematician, Adrian Metius. Fifteen days after Lippershey applied for his patent Metius made a similar application, stating that he had discovered how to make these instruments two years earlier, while engaged in some optical experiments. In the interval, he asserted, he had been making telescopes at least as good as those offered the state by Lippershey.

A third claimant was Zacharias Jansen, a Middelburg optician like Lippershey. Jansen asserted that he had invented the telescope with his father, Hans Jansen, who is believed to have been the inventor of the compound miscroscope. Perhaps as early as 1590 the Jansens were experimenting with lenses and tubes, with the idea of magnifying objects close at hand. It is

possible indeed, the principles of the microscope and telescope being similar, that they did actually make one of the latter.

But if so, nothing came of it, and to Jan Lippershey must be given the credit of giving this instrument to the world. The curious thing, after all, is not that one or the other of the claimants discovered the principle of the telescope, but that this discovery was so long delayed. The materials of those first instruments were in the shop of every optician in Europe, and for at least three centuries the art of making lenses for spectacles had been carefully cultivated all the way from Italy to Germany and England.

Why is it that no spectacle-maker in previous times had hit upon that one correct combination, and so provided astronomers with telescopes centuries earlier? There is no certain answer to this question, but Dr. Louis Bell, in his book *The Telescope* (McGraw-Hill) advanced an interesting theory that may be very close to the truth. The early opticians, whose profession goes back at least to the year 1289, dealt only with the simplest kind of eye defect, far-sightedness, "the common and lamentable affliction of advancing years."

The opposite kind of eye defect, nearsightedness, would naturally be rare in a period of general illiteracy, and glasses for its correction, especially in the higher degrees, would be in such small demand that few opticians would have them. For far-sightedness convex lenses of moderate power sufficed; but in the absence of nearsightedness there would be lacking the second type of lens, the concave, needed to provide an eyepiece for the Lippershey type of telescope.

Hence it may be that astronomers have to thank the spread of learning through Europe, with its concomitant aggravation of eye defects, for the invention of the instrument that was to set them free of the old, small heavens.

II

If the world waited three unnecessary centuries for the invention of the telescope, it was not so long in making use of it once the discovery had been made.

News of the miraculous power of these new Dutch instruments spread rapidly over Europe, and it is perhaps fortunate for Lippershey that he did not receive a patent from the States-General for his invention, else he would have had to spend the rest of his life in fighting infringements. Spectacle-makers quickly fathomed the secret of the instrument. They were soon on sale in Holland, Paris, Milan and London, and by 1610 were being made in England—under the name of "Dutch trunks."

Less than six months after Lippershey applied for his patent, travelers had brought word of the invention to Italy, and in May, 1609, certain persons in Venice learned that with the aid of two pieces of glass and a paper tube distant objects could be brought close for inspection. It happened that the great Italian scientist Galileo was visiting in Venice when this momentous piece of information arrived. Within a few days he received confirmation of it from a friend in Paris, and immediately returned to his home at Padua to construct a telescope for himself.

Galileo appears to have been the first to grasp its astronomical possibilities. Earlier users had contented themselves with looking at church steeples, the doings of people across the way, and the adaptation of the telescope to military uses. Galileo's scientific mind saw at once a greater field of usefulness than any of these, and the anticipation of celestial views to come drove him to finish his first telescope with almost unbelievable quickness.

It is related that he had solved the principle of the instrument by the night of his return to Padua, and made his first instrument the next day. Since the work of fashioning the lenses would mean delay, he went the rounds of the spectacle shops until he found what he wanted: a good convex lens for his object-glass, and a concave one of short focus—the kind that might have been used in correcting a very severe case of short-sightedness—for his eyepiece.

This first telescope he finished by inserting the lenses at the proper distance in opposite ends of a leaden tube. They were of the type known as plano-convex and plano-concave—that is,

one side of each was flat; the curvature was on the other. Viewed through this telescope objects appeared only one-third their actual distance away, and nine times larger than when seen with the unaided eye.

This success caused him to redouble his efforts, and shortly he was rewarded with another telescope that magnified eight diameters. But now he could no longer depend on the lenses supplied by spectacle-makers; such glasses were not strong enough or sufficiently well made for his purpose. He began to grind lenses himself, experimenting with different combinations. At length he produced a telescope capable of magnifying about thirty diameters—the practical limit with a simple instrument of the Galilean type. It was a rather miraculous achievement, considering that he had no good optical glass, no adequate method of grinding or centering the lenses, and neither theoretical nor practical experience in optics to guide him.

III

Despite difficulties, a glass of suitable power for astronomical observation was now in his hands! It is not hard to imagine the excitement which must have attended his preparation for that first exploratory venture amid the new and invisible heavens—a venture beside which the penetration of a new continent, the transmutation of base metal into gold, even a visit to another planet would have seemed insignificant to an astronomer.

He says: "I betook myself to observations of the heavenly bodies; and first of all, I viewed the moon as near as if it were scarcely two semi-diameters of the earth distant. After the moon, I observed other heavenly bodies, both fixed stars and planets, with incredible delight."

The moon, he found to his intense interest, was no polished, perfect sphere, but a rough, pitted ball; like the earth in so many details that he was filled with astonishment at this discovery. He, Galileo Galilei, humble professor of the university of Padua, was the first man in all the world to look upon the face of the moon and know it for what it was: to see what appeared to be the craters of dead volcanoes, to see the sunrise glistening brilliantly from a lunar mountain peak while the valley still lay in darkness beneath it! "The grandeur of such prominences and depressions in the moon seems to surpass both in magnitude and extent the ruggedness of the earth's surface."

But he must not linger too long on the wonders of this new face of the moon. He swings the glass this way and that, taking in all the miracle of the heavens as a starving man, released at last in a well-stocked pantry, samples first one food and then another, cramming his mouth so full he has no time to chew or swallow.

Leaving the moon, Galileo notices that there is a difference in appearance between the fixed stars and the planets. Hitherto the only observable variation, aside from brightness, has been that planets wander about the heavens; stars do not. But now Galileo, pointing his marvelous new telescope upward, sees that the planets present perfectly round discs; they are worlds. They appear "as so many little moons, completely illuminated and of a globular shape." But the fixed stars are not similarly bounded by a circular circumference. Even in the telescope they are blazes of light "shooting out beams on all sides and very sparkling, and they appear of the same shape as when viewed by simply looking at them, but so much larger that a star of the fifth or sixth magnitude seems to equal Sirius, the largest of all the fixed stars."

Now Hipparchus, in classifying the stars according to brightness, had sorted out the largest among the stars and placed them in the first magnitude; the next brightest in the second, and so on down to the sixth magnitude, which are the faintest stars of all, and no fainter can be seen with the naked eye. The number of stars in these six magnitudes is relatively small—certainly not more than a man might count if he were to set out diligently to do it.

But now, as Galileo sweeps the heavens with his magical instrument, he sees that the stars comprise an infinite multitude:

"Beyond the stars of the sixth magnitude you will behold through the telescope a host of other stars, which escape the unassisted sight, so numerous as to be almost beyond belief, for you see there more than six other differences of magnitude, and the largest of these, which I may call stars of the seventh magnitude, or of the first magnitude of invisible stars, appear with the aid of the telescope larger and brighter than stars of the second magnitude seen with the unassisted sight."

Even this is not the end of the wonders disclosed on the balmy spring evenings at Padua by the necromantic tube through which Galileo viewed the heavens. He turns his attention next to the Milky Way, and there to his eyes comes the answer to an age-old question—an answer that settles once and for all the disputes which have tormented philosophers through so many ages. For the Milky Way, that filmy strange band of cloudy luminescence, is really nothing but a mass of stars planted together innumerably in clusters: "Upon whatever part of it you direct the telescope straightway a vast crowd of stars presents itself to view; many of them are tolerably large and extremely bright, but the number of small ones is quite beyond determination."

IV

Until after all this was reserved the most remarkable discovery of all; a discovery which at once should confound the critics of the system of Copernicus and answer a question that even the friends of that embattled theory had been puzzled over. How does it come, they ask, that tho all of the planets travel around the sun, our earth nevertheless has a planet indisputably traveling around it? Does not the motion of the moon upset the system, and cast doubt upon the whole theory?

Galileo, moving his telescope across the heavens to observe the fixed stars, comes accidentally upon the giant of the planetary system, Jupiter. Pausing for a moment to watch the bright round disc of this fellow, he is puzzled to observe three little stars, small but very bright, near the planet, arranged in a straight line parallel to the ecliptic, brighter than the rest of

the stars of equal apparent magnitude. On the east side of Jupiter there were two of the stars, on the west but one.

On the following night, that of the 8th of January, 1610 (six or seven months after Galileo began observing with his telescope) he again turned to that part of the heavens, and found a very different and most surprizing state of things, for now the three little stars were *all west* of Jupiter, whereas before two had been on the east side. On the 10th of January he viewed them again. This time there were only two of the tiny stars visible. Both were on the *east* of the planet, tho still on the plane of the ecliptic.

Here were no ordinary stars! These were planets, moving not around the sun but around Jupiter—positive evidence that the largest of the family of the sun has not one moon, but at least four. What better proof could the Copernican theory ask for? In Jupiter's moons we may see with our own eyes a planetary system in full operation!

These Jovian satellites Galileo named "Medicean planets," after the family at that time powerful in Italy. With their astounding discovery his important voyagings into the heavens were by no means at an end. One day he turned the instrument on the sun itself, and perceived that that luminary is no more perfect than the moon. Even the sun has spots on its face! These spots, moreover, gave him an opportunity to study the motions of the sun, and to conclude that it is steadily rotating.

Then came the final bit of evidence, if any were still needed, to prove the correctness of the Copernican theory. He saw Venus in her phases like the moon, proving that she is a planet like the earth, cool and shining by reflected light from the sun, and moreover, that she is in motion around the sun, and presents the phases suitable to such a motion.

V

Galileo was not the kind of man to keep his discoveries and his theories to himself, even if he had known the personal danger incurred in revealing them. As soon as he had com-

pleted a presentable telescope, he took it to Venice, where he made public the nature of the device and proclaimed the wonders that could be seen with it. Officials, students and important personages of all kinds gathered to peer through it. In the end Galileo presented the instrument to the doge Leonardo Donato.

In return for this gift and the honor he had brought upon the University of Padua, the Senate settled him for life in his lectureship there and doubled his salary. His subsequent amazing discoveries brought him great notoriety and admiration throughout Italy, and went ringing throughout Europe, clothed in language filled with the enthusiasm Galileo himself felt for the marvels his glass was disclosing.

Such popularity was bound to bring him enemies as well as friends. Presently there were disputes as to the priority of some of his discoveries, notably that of the sunspots. It was pointed out that the astronomer John Kepler, pupil of Tycho Brahe, had actually seen a sunspot, even in pre-telescopic days, by casting the image of the sun through a hole in a disc upon a screen. Kepler, however, had not recognized the spot for what it was, but assumed that he was witnessing a transit of Mercury across the sun's disc.

There were others whose claims rested on better evidence. Several astronomers, among them Johann Fabricus and a Jesuit priest, Christopher Scheiner (of whom we shall hear more presently), apparently made the discovery of sunspots independently at about the same time as Galileo. Scheiner was a vindictive sort and very loud in his claim upon the sunspots, which he observed at some length and wrote about voluminously. There is reason to believe that Scheiner may have been partly responsible for the persecution which presently began to be directed toward Galileo, but he was by no means the only cause; perhaps not even an important one. The Church, so long dormant while the growing tide of belief in the system of Copernicus rose throughout Europe, at last took direct action against the theory, the book in which Copernicus explained it, and those who professed belief in the pernicious doctrine that the earth moves around the sun.

In 1616, seventy-three years after the first copy came off the press, the great work of Copernicus, *De Revolutionibus Orbium Cœlestium*, was placed on the *Index Expurgatorius* and all Catholics forbidden to read it. It must be remembered that this was at least six years after Galileo had supplied visual proof of the theory by his discovery of the moons of Jupiter and the phases of Venus, and sixteen years after the martyr Giordano Bruno had been burned at the stake as an object lesson to those who taught that the sun and not the earth is the center of the universe. The answer of the ecclesiastical authorities at Rome to Galileo's proof of the Copernican theory, was to summon him to answer for his conduct.

Many have professed to find the Italian astronomer wanting in character for what took place at that momentous interview. But it is not so hard to understand, and many a man not a fanatic would have acted as he did under the circumstances.

Galileo at this time was seventy years old. He had led an honored, exciting, useful life; yet he had no taste for the tortures of the Inquisition or the bloodless death of Giordano Bruno. When it was demanded of him, as an alternative, that he renounce publicly and under oath "the heresy of the movement of the earth," he did so. And if he did not mutter under his breath, as legend has it, *"E pur si muove!"* ("Nevertheless, it moves!") he must most certainly have had it in his mind.

VI

Galileo's instruments (to which he gave the name telescope) were strictly limited in size. This was due to several technical difficulties which the Italian probably did not clearly understand, and which he could not have corrected with the materials available to him had he done so. From first to last he used the same combination of lenses; convex for the objective, concave for the eyepiece.

Farther north, at an observatory near Prague which Tycho Brahe had built shortly before his death (not Uraniborg, and far from equaling it in splendor), Kepler was at this time

engaged in the laborious task of completing the famous Rudolphine Tables of the planetary motions, started by his illustrious predecessor and named in honor of the Austrian Emperor Rudolph II.

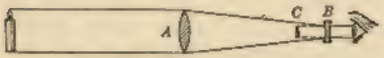


Fig. 7
Scheme of Galileo's Telescope. It consists of a convex objective lens A and a concave eyepiece B, placed just inside the focus of A. The object is seen right side up, but the field of view is small, as indicated by the apparent image C.

This ingenious scientist, discoverer of the laws of planetary motions he deduced from his own observations and the wealth of data left him by Tycho Brahe, obtained about 1610 one of the Galilean telescopes which at that time were setting all Europe abuzz with excitement and interest. He immediately began to observe the wonders of the heavens with it, and was disappointed by its limitation as to power and the smallness of its field of view.

Pausing for a time from his prodigious astronomical labors, Kepler made a thorough study of the telescope. In the light of what he had learned about the general theory of optics he was able to perceive the reason for the Galilean telescope's limitations, and moreover, to suggest an improvement.

As we have seen, the telescope devised by Lippershey and used by Galileo consisted of a convex outer lens, or objective, and an inner concave lens. In order to work this combination, it is necessary to place the eyepiece lens just inside the focus of the objective, as shown in Fig. 7. Hence no real image is formed in the telescope; the device merely brings the pencil of light down to the diameter of the pupil of the eye and passes it on to the crystalline lens and retina. This imposes a strict limitation on the field of view, for the effective part of the concave eyepiece is only that portion handling light which passes into the eye. If this lens is enlarged to widen the field, it makes no difference, since the extra light will fall outside the pupil and hence will be wasted.

The Galilean lens combination is still used in inexpensive opera glasses, and the restriction of the field of view is always noticeable in them.

It was Kepler's simple suggestion that this difficulty might be overcome by using, instead, a convex lens of very short focus for the eyepiece, placed in such a way that the objective and eyepiece are separated by an interval equal to the sum of their focal distances (Fig. 8). It is true that in Galileo's telescope the image appears conveniently rightside up, whereas in the Kepler instrument it will be inverted, but for astronomical purposes this is a matter of small moment. It is more than balanced by the wide, clear field, and in fact the Keplerian arrangement, with slight modification, is that in use in many large astronomical telescopes today.

Kepler never actually made a telescope of his improved design. It fell the lot of that same Jesuit who had taken issue with Galileo over the sunspots, Christopher Scheiner, to construct the first Keplerian telescope. Moreover, this man was probably the first astronomer to mount his telescope on a polar axis (Plate 5).

Scheiner was a professor of mathematics at Ingoldstadt. Despite the many quirks of personality that annoyed his contemporaries, due credit must be given for the work he did in observing the sunspots, and also for the early improvements to the telescope which he introduced. It is true that none of them were in any real sense original; nevertheless this astronomer was first to see the importance of the Keplerian telescope and the equatorial mounting, and his writing brought them to the attention of all the other astronomers of Europe.

Fig. 8
Scheme of Keplerian Telescope. It has a convex lens of short focus for the eyepiece, placed outside the main focus in such a way that the image C, formed by the objective glass A, is magnified. This arrangement provides a wide field, but the image is inverted.

Scheiner also invented an improvement of his own; a kind of telescope made especially for viewing the sun, and called by him a "helioscope." It was simply a tele-

scope in which the objective lens was made of colored glass, to cut down the glare. Tho the mathematician of Ingoldstadt found it useful, it has not survived; hence it was not so much an improvement as a novelty.

Chapter IV

THE TELESCOPE HAS GROWING PAINS—SOME QUEER ONES APPEAR

I

IT would seem as if the practitioners of the new telescopic astronomy were now in excellent position to make conquest of the heavens. Galileo had shown what could be done even with a small instrument, and Kepler had suggested an improvement which opened the way to the construction of large and powerful ones.

But the Keplerian telescopes, while eliminating the difficulty with the Galilean type, introduced a new train of woes. Chief among them were those twin banes of the seventeenth-century telescope-makers—*spherical* and *chromatic* aberration. In Galileo's telescopes these troubles did not appear to an extent great enough to be noticeable. But when the followers of Scheiner imitated his example and made Keplerian telescopes —and made them with larger lenses to let in more light—the disturbing disease-like aberrations began to appear.

The trouble was all the more infuriating because so mysterious. Why should small telescopes work perfectly, and larger ones, made on exactly the same pattern, blur the image, and provide an unpleasant and distracting fringe of color around it?

We can well imagine the puzzlement of early astronomers at this question. It must be remembered that the study of lenses was then so new it hardly merited the name of a science. No established body of knowledge of the behavior of light was in existence upon which to base such a science. What was light? Nobody could say. Tho there were many theories, most were mystical or fantastic, or so colored with the theological views of the time as to contain no science whatever.

If, today, we are inclined to feel a bit superior in our greater knowledge of these matters, we have only to remember the puzzlement of contemporary scientists over the origin and behavior of the cosmic rays to realize the bewilderment with which telescope-makers of the early 1600s approached the knotty question of aberration.

For all that, the cause of their troubles is quite simply explained. As the name suggests, *spherical aberration* was due to the shape of the lenses used by the first telescope-makers. These bits of glass were always provided with one or more curvatures which were parts of the surface figure of a great sphere (Fig. 9).

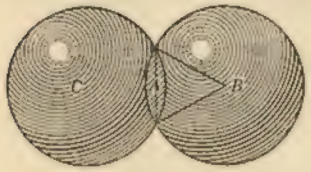


FIG. 9

Curvatures of a double-convex lens. The surfaces of the lens A are parts of the surfaces of the spheres B and C, hence are *spherical* curvatures.

Now it can be shown that simple lenses of spherical curvature cannot focus all the rays of a parallel beam of light (such as that coming from a very distant object) to one sharp point. The light falling on the outer part of the lens, where the glass is most curved, will be slowed more, hence given a greater bend, than that falling at the center. The beams striking on each zone will be brought to focus at a different point. The focus of the lens, instead of a point, will be a line (Fig. 10), resulting in an image of poor definition, no matter how carefully the objective is ground or how clear the glass.

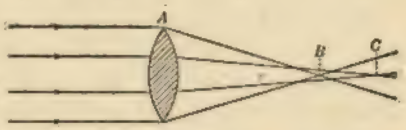


FIG. 10

The Cause of Spherical Aberration. A simple spherical lens A cannot focus all the light of a parallel beam sharply at one point. That falling on the outer parts of the lens will be bent more than that falling nearer the edge. The beams falling on each zone will be brought to a different focus, as at B and C.

It is apparent that a *concave* lens of spherical curvature will display spherical aberration, too, but in the opposite manner. The light falling on the inner,

thinner part of the lens will be bent most; that toward the edges least. This explains why astronomers were not troubled with spherical aberration in Galilean telescopes. The spherical aberration produced in the convex object-glass was substantially canceled out by that produced in the concave eyepiece, resulting in a sharp final image.

In the Keplerian telescope the spherical aberration produced by the objective is not so canceled out; it is exaggerated by the similar curvature of the eyepiece. Hence, while producing a wide field of view, Kepler's telescope acted to destroy the sharpness of the image in that field, and was a troublesome and puzzling instrument in many ways.

II

A solution to this knotty problem was thirty years in coming —years during a major part of which earnest and devoted astronomers were doing their best to chart and explore the invisible heavens with stubborn and unsatisfactory instruments of many varieties. It was a scientist already well known who hit upon the true cause of their troubles and made suggestions looking toward improvement.

He was the French mathematician and physicist, René Descartes, who in 1637 published his famous *Dioptrica*, establishing the new science of lenses upon a secure foundation. In this work Descartes clearly explained the cause of spherical aberration, and showed that it might be overcome in two ways. One method would be to reconsider the shape of the lenses. Obviously they should not be spherical, for the spherical lens cannot wholly concentrate parallel rays. Rather, the figure should be elliptical or hyperboloidal; both kinds most difficult to make, but nevertheless required if the fundamental problem of spherical aberration were to be solved by the method of improving the curvature.

But if lens-makers could not for the time being fashion these difficult curves (and it was safe to assume that unless new methods of grinding lenses were perfected they could

not), then, said Descartes, let them make their objectives with as little curvature of any kind as possible; in other words, increase the focal length. The spherical aberration, while not entirely eliminated, would then be much less.

FIG. 11

The Cause of Chromatic Aberration. The many colors contained in a beam of white light L are differently bent in the lens A, the blue light focusing at B, the green at G and the red at R. If the image is viewed at B it will be surrounded by a red and green fringe; if at G, by a blue and red fringe, and if at R, by a blue and green fringe.

Both of these suggestions were sound, but as we have seen, one was unworkable in practise. Lenses ground with elliptical or hyperboloidal curvatures are rare and exceedingly difficult to make to this day, even tho the artist in lens-making who attempts such delicate work is equipped with the finest modern tools for it. In the time of Descartes it was wholly impossible, for the difference between the true sphere and the correct hyperbola is too minute to be measured by other than optical means, and the working of the figure a matter of the most exquisite craftsmanship, plus adequate mechanical appliances and the best kind of optical glass.

On the other hand, longer telescopes could be made almost at once, and without changing current methods of lens grinding. Longer telescopes have less spherical aberration for the reason that the amount of aberration is directly proportional to the thickness of the lens due to its curvature. The longer the focus, the thinner the lens, hence the less the aberration.

As for *chromatic* aberration, this phenomenon must have been puzzling to Descartes, for even the great French physicist did not understand the nature of color, or the fact that many colors are contained in white light. It was reserved for the Englishman Newton to disclose this fact, more than half a century later.

Chromatic aberration is due to the prismatic effect of the lens—its power to produce *dispersion* of the colors contained in

white light. It appears because the various colors of light are affected differently by passage through glass, hence are bent through slightly different angles in the lens. In a spherical lens of homogenous material the blue light will receive the greatest bending, hence will come to a focus nearer to the lens than the red or green rays (Fig. 11).

This kind of aberration appears in the telescope as a fringe of color around the image, and the fringe may be so distressingly wide as to destroy the definition. Descartes probably had no notion whatever that he was dealing with two kinds of aberration, but by sheer chance his suggestion for correcting spherical aberration also is a material aid in overcoming the other kind, which otherwise would have been very troublesome in those early telescopes. While the amount of chromatic aberration is substantially the same no matter what the thickness of the lens due to curvature, a longer focus serves to enlarge the image, hence the color fringe is *relatively* less.

III

Actual improvement in telescopes did not follow immediately upon publication of Descartes's suggestion, as might have been expected. To be sure, telescopes became moderately longer—up to about six or eight feet, and there were many undiscovered and uncharted things in the heavens that could be seen and measured with these modest instruments. The construction of larger ones was difficult and exacting work, and any journeyman astronomer could not manage it. The telescope was awaiting the arrival of an artist who would be able to grind the better lenses, and an engineer who could master the details of adequate mounting.

A decade passed before such a man appeared, and when he came it was a curious coincidence that he should be a fellow-countryman of Jan Lippershey. He was the famous and able Dutch astronomer, mathematician and physicist, Christiaan Huygens—the same who was destined later to build some of the world's biggest telescopes, rediscover the principle of the

pendulum clock, and provide the fundamentals of a wave-theory of light.

It was not zeal for improvement of the telescope itself ("noblest invention of our Belgic nation," he called it) that attracted Huygens to the difficult art of making lenses, but rather an intense longing to view with his own eyes the remarkable appendages which Galileo and other astronomers had observed on the planet Saturn. Such phenomena must surely, Huygens thought, be resolved in more explainable terms by more powerful telescopes, but he had at the time "only the ordinary form of telescope, which measured five or six feet in length."

He therefore set to work, aided by his brother, Constantine, to learn the art of making telescopes. As they studied it they were taken with that subtle, recurrent fever for battle with stubborn glass which has infected many an astronomer and telescope-maker since their time, and which is the true sign of a gift for this exacting and fascinating art. In short, while remaining astronomers, the Huygens brothers also became first-class telescope-makers. There is a question as to which they found the more exciting: making telescopes or viewing the marvels of the heavens through them.

Christiaan Huygens' first usable telescope, upon which he began work about 1650, showed that he had resolved to put into practise the principles taught by Descartes. It was twelve feet long—nearly twice the focal length of the longest ordinary instrument of its day. Moreover, it contained some of the finest lenses ever fashioned, and was so powerful that Huygens immediately made with it two of the most astonishing discoveries of the age.

Directing his new instrument toward Saturn, he was able to see that this planet, like Jupiter, is the center of a miniature planetary system. At least one moon, far out from the planet, appeared clearly in Huygens' twelve-foot telescope. He was able to determine with certainty that the tiny flying satellite revolves around its principal in sixteen days.

But this was not the matter of greatest importance. When Huygens swung his telescope to bear directly on Saturn himself, he beheld there something that brought his breath up short. For it appeared that the two neighboring appendages clinging to Saturn, which Galileo and others had thought were moons so close to the planet that they were in fact touching its sides, were not moons at all, but something most astoundingly different. Huygens saw, as he gazed through his fine new telescope on the fifth day of March, 1656, *that Saturn was encircled "by a ring, thin, plane, nowhere attached, and inclined to the ecliptic!"*

News of this discovery spread over Europe like wildfire, once the Dutch astronomer felt sure enough of his ground to announce it. With it went the fame of the marvelous new twelve-foot telescope. Astronomers began to desire such instruments for themselves, and inquire where they might be obtained. Professional telescope-makers in Italy, England and Holland pricked up their ears at the word, and for the first time saw a great light. So there had been something to that notion of Descartes, after all!

Presently long telescopes began to appear everywhere. Englishmen made them; Italians tried their hand at them; they were produced in France and Holland. Some were very good, some fair; most of them mediocre and many very bad. For tho they could lift Huygens' idea and follow his methods, it was a very different thing trying to copy his way with glass. Only an artist could do that, and artists are rare.

IV

The great Dutchman and his brother soon resumed their work. Christiaan Huygens' experience with the twelve-foot telescope had whetted his desire for longer ones.

And if twelve feet seemed long to astronomers then, what must they have thought of the ones that followed? It was not many months before a twelve-foot Huygens telescope would have been considered an instrumental pigmy. The Huygens brothers were out to push the telescope to the limit. They

began to grind lenses with such slight curvature that they were almost flat discs. The focal lengths became greater and greater. Twenty-foot telescopes were common; thirty-foot ones began to be seen; there were even some forty and fifty feet in length.

They were not long alone in this noteworthy endeavor. A few other men in Europe were becoming almost as skilled in making instruments as Christiaan and Constantine.

Over in Danzig lived one of them, an astronomer named John Hevel, or Johannes Hevelius, as he preferred to be called. Hevelius had begun his career with a detailed and complete study of the moon. In 1647 he published his great treatise on the earth's satellite, the *Selenographia.* It was the first systematic study of the moon, and replete with such fine and detailed maps of the lunar landscape that it set the pace for all studies of the moon for many years.

In the *Selenographia* Hevelius gives an interesting account and description of the astronomical instruments in use at that time. He tells with great care how to make various pieces of equipment such as he used in his studies, describing in detail both the Galilean and Keplerian types of telescope.

One of the principal problems in making these instruments, remarks Hevelius, is finding suitable material for the tube in which the lenses are held. The earliest makers often employed paper for this purpose, but the astronomer is advised against this material because of its fragility and lack of durability. Tubes of iron also were frowned on, chiefly because of their weight and costliness. Hevelius' preference was for wood, which is both cheap and durable, and tho heavier than paper, nevertheless is lighter than iron.

As for the length of the instrument, Hevelius suggests in the *Selenographia* that a superior image might be obtained with a telescope twelve feet long, but for the most part the instruments he describes are shorter. It was only after the success of Huygens that Hevelius joined the race which soon absorbed almost every telescope-maker in Europe—the contest to see who could build the longest, unwieldiest telescope.

"Since it is now accepted as a proved fact that nothing furthers the interests of science more than the use of accurate and perfect telescopes, by means of the numerous celestial observations they record, every astronomer and optician of the present day wishes nothing more heartily than to make them more perfect and of greater length," he wrote in a later book, the *Machina Celestis,* published just before the disastrous fire that destroyed his observatory in 1679. In this most curious work, which is mainly a collection of descriptions of instruments, Hevelius relates how he himself constructed a telescope 150 feet long, up to that time the champion.

Now the grinding of perfect lenses of such slight curvature is a sufficient task in itself. It is easier to put a large curvature on glass than a relatively slight one, and the production of a perfectly *flat* surface is perhaps the hardest task of all.

But the astronomer of Hevelius' time found, when he had ground an object-glass of 150-foot focus, that his real difficulties had only begun. For how could one manage the mounting of such a monstrous, slender instrument? Iron, tho stiff enough for the tube, was too heavy and expensive. A simple wooden tube, such as proved satisfactory for shorter telescopes, up to say fifty feet, was out of the question by reason of its lack of stiffness. Only the slightest bending would throw the lenses out of line.

The upper picture in Plate 6, taken from the *Machina Celestis,* shows how Hevelius met this problem. Note that it is an "aerial telescope," as these reedy instruments without tubes came to be called. The stiffening for the mounting was provided by two planks fastened at right angles to each other along the edge, to form a lengthy trough. This in turn was stiffened and braced with wires, and swung into the air with the aid of pulleys and tackle.

At the upper end of the contrivance perched the objective, casting its long beam down the trough to the eyepiece at the lower end. On the way the light passed through circular openings cut in a series of wooden diaphragms. The purpose of these was to provide further stiffness to the instrument, and more

especially to protect the image from stray side-light that might otherwise come down the tube with the rays from the objective.

The problem that confronted an astronomer attempting to use such an instrument is made amply clear by Hevelius' drawing. The very erection of an aerial telescope was something of a neighborhood event, like a balloon flight or excavating the foundation for a new building. Immediately an astronomer brought his telescope out of its hangar a crowd would begin to gather. This was well, too, in its way, since plenty of help would be needed, volunteer or otherwise.

Hevelius depicts *his* telescope-raising as something more than a community affair, for we can see clearly that members of the nobility are present. In the left foreground a stately introduction is going on, and in the background is the coach that has brought a notable to the scene. The astronomer himself is hovering solicitously near the eyepiece of his instrument, probably shouting directions to the assistant obediently tugging at the rope, elevating the telescope. Apparently the whole affair is taking place in broad daylight; it is hard to see how it might have been otherwise. Imagine the task of getting that huge affair aloft at night, without the aid of modern floodlights!

This feature of the long telescope—its unmanageability—does not escape complaint in Hevelius' book. Consider the arduous task facing an astronomer who wishes to make a few observations of a fine summer evening: he must take his telescope out of the warehouse in sections, transport it gingerly (for such instruments are necessarily frail) to the field where his telescope mast has been set. He must enlist the aid of a gang of strong fellows to pull on the ropes and help him swing the instrument into place.

Moreover, he must be something of a tackle expert as well as an instrument-maker and astronomer. He must at least know how to put the sections of the long trough together, and how to take them apart again.

Finally, after each session with the stars the telescope must be put away with the most scrupulous care, else it will be useless on the next occasion. And if, while he is observing, a sudden

shower should come up, or a wind, his instrument may be wrecked or warped and ruined in the twinkling of an eye; long before he can get the slender apparatus down off its high perch and back into the safety of its shelter.

"There should be some prince, some great Mæcenas of celestial studies," cried Hevelius (an utterance that must have raised echoes in the heart of every astronomer of his day). "Under such conditions I feel that an observatory might be founded and fitted up to which access to the best-constructed and most-perfectly-fitted telescopes shall be possible at all seasons and all weathers, as often as may be agreeable. Where, whether the telescope be twenty, forty, sixty, a hundred; nay, a hundred and fifty feet long, you shall have nothing more to do, as the guiding ropes will always be hanging down ready for use, than to elevate any telescope you please; nay, two or three of the largest size at once, and point them to the stars; and again, whenever you please, at once to restore them with all their tackling, whole and uninjured, to their proper receptacles, a place where they may severally remain secure from disturbance."

When he wrote this, Hevelius was indulging, of course, in a gorgeous day dream. What might he say if he were to come back today, and see the great observatories of the world, where wonders such as he was unable even to imagine, and conveniences beyond his ability to conceive, aid the astronomer in his nightly voyaging among the stars?

A marvelous observatory of the future, as the astronomer of Danzig visioned it, is depicted in Plate 6 (lower picture, also from *Machina Celestis*). It shows three astronomers hard at work on the upper platform, their telescopes slung to tackle from the central tower. Down below in the shelter expert workmen are assembling a fourth instrument, which will presently be hoisted through the horizontal slot in the foreground and put to work.

V

In spite of the difficulties, the procession of longer telescopes continued. Christiaan Huygens made one of 123-foot focal

length and presented it to the Royal Society, which still has it, together with two telescopes, even longer, also made by Huygens. One of these has the astounding length of 210 feet, another 180 (Plate 7).

Not to be bested, the telescope-maker Adrien Azout produced even more formidable ones, ranging up to 300 feet or more. The telescope-makers of Italy, especially Divini of Rome, and Campani, who made the first telescopes of the Paris Observatory, also turned out some lengthy instruments of first-class workmanship. In England the telescope-makers were equally busy; some authorities state that telescopes as long as 600 feet were manufactured there.

But did these slender beanpoles of instruments produce any results commensurate with their length and awkwardness? It almost goes without saying that they did not.

When Christiaan Huygens completed his work on the rings of Saturn and made his fine contributions to knowledge of the planet Mars, it was not with one of his giants but with a telescope of only 23-foot focal length.

Dominique Cassini, working at the Observatory of Paris in the '80s of the seventeenth century, found two new satellites of Saturn with Campani's telescopes of 100- and 136-foot focus respectively. But previously he had made equally interesting finds: the satellites Iapetus and Rhea, with shorter telescopes of only seventeen and thirty-four feet. The discovery to which Cassini's name is most often attached, the famous division in the ring of Saturn, is said to have been made with a twenty-foot telescope bearing a magnifying power of only 90 diameters.

Other astronomers of the period also found smaller telescopes more productive than the long ones, however much better the latter were in theory. The most remarkable accomplishment ever made with a telescope of great length, in fact, was the measurement of the diameter of Venus, achieved on December 27, 1722, by the British astronomer James Bradley, with a telescope 212¼ feet long.

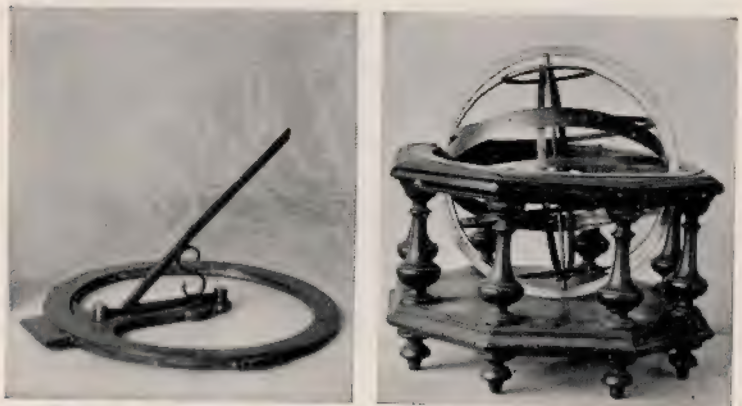
Photo by Robert Yarnall Ritchie, Courtesy Corning Glass Company

TESTING A GATEWAY TO INFINITY
Dr. George V. McCauley, physicist, examining the disc of the 200-inch telescope mirror with a polariscope at the Corning Glass Works

[PLATE 1]

David Eugene Smith collection, N. Y. Museum of Science and Industry

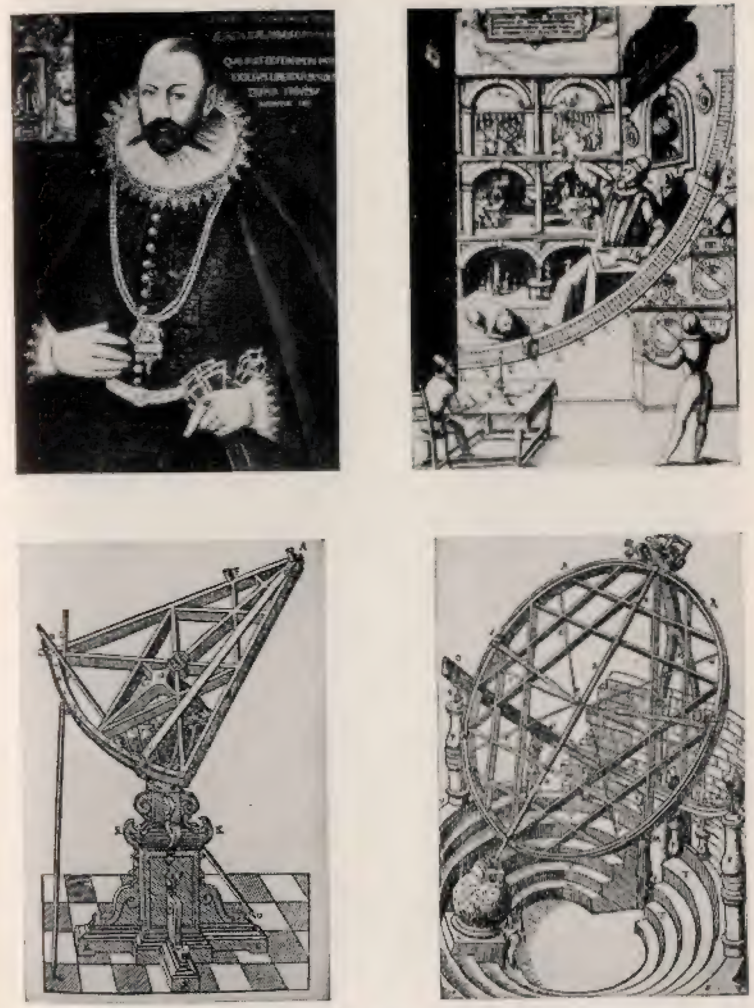
ASTROLABE OF ITALIAN WORKMANSHIP, ABOUT 1558—FRONT VIEW AT RIGHT, BACK AT LEFT



David Eugene Smith collection, N. Y. Museum of Science and Industry

RIGHT—AN ARMILLARY SPHERE OF ITALIAN WORKMANSHIP, ABOUT 1550; LEFT—SMALL PORTABLE SUNDIAL

[PLATE 2]



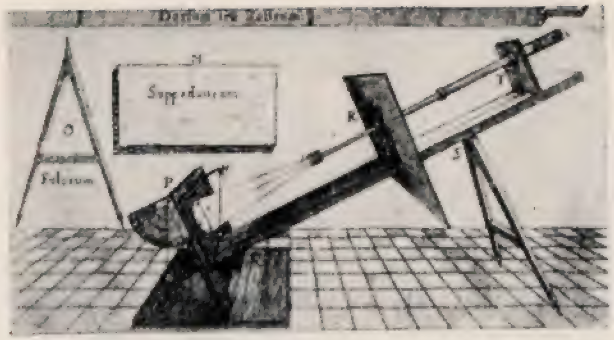
TYCHO BRAHE AND SOME OF HIS REMARKABLE INSTRUMENTS

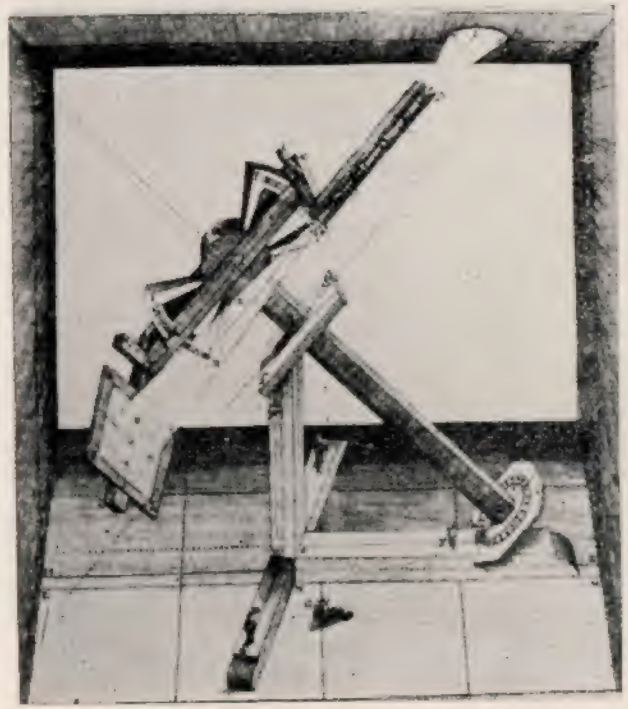
Upper right, Mural Quadrant at Uraniborg; lower left, sextant; right, equatorial armillae

[PLATE 3]

JAN LIPPERSHEY, INVENTOR OF THE TELESCOPE (LEFT) AND GALILEO (UPPER RIGHT)
With two of Galileo's telescopes as they appear today in the Museo di Fisica e Storia Naturale, Florence, Italy

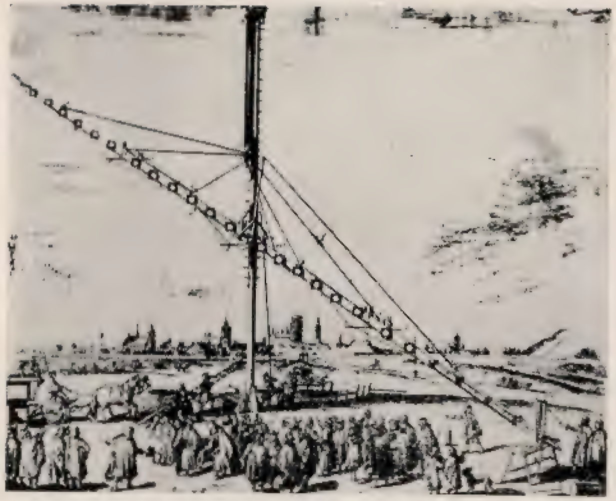
[PLATE 4]



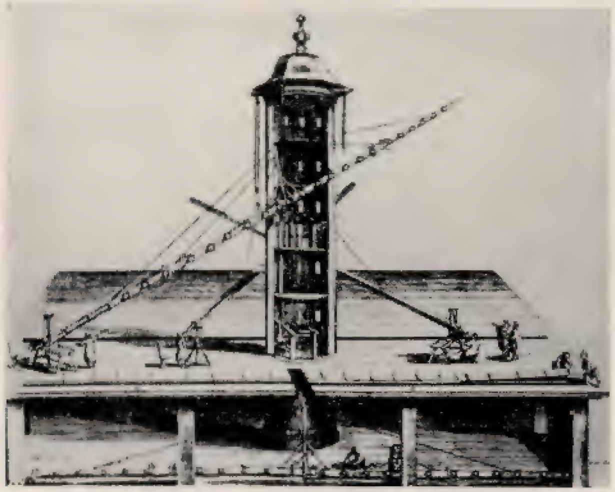


CHRISTOPHER SCHEINER'S TELESCOPIC INSTRUMENTS
The first equatorial telescope (below) and the "helioscope"

[PLATE 5]



HEVELIUS'S 150-FOOT TELESCOPE



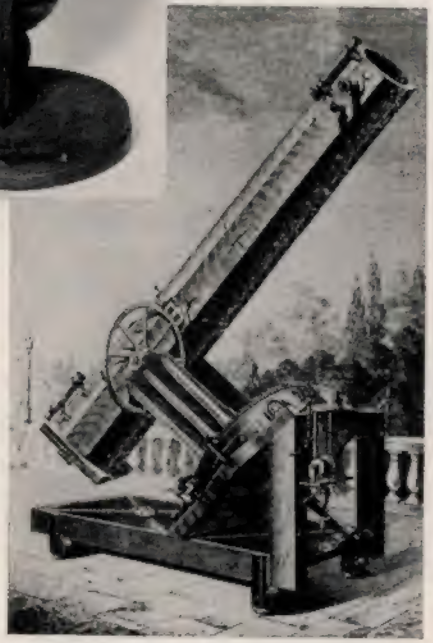
HEVELIUS'S PLAN FOR AN "IDEAL" OBSERVATORY

[PLATE 6]

CHRISTIAAN HUYGENS AND ONE OF HIS "AERIAL" TELESCOPES

[PLATE 7]

NEWTON'S SECOND REFLECTING TELESCOPE AS IT APPEARS TODAY



AN EARLY SILVER-ON-GLASS REFLECTOR MADE BY FOUCAULT

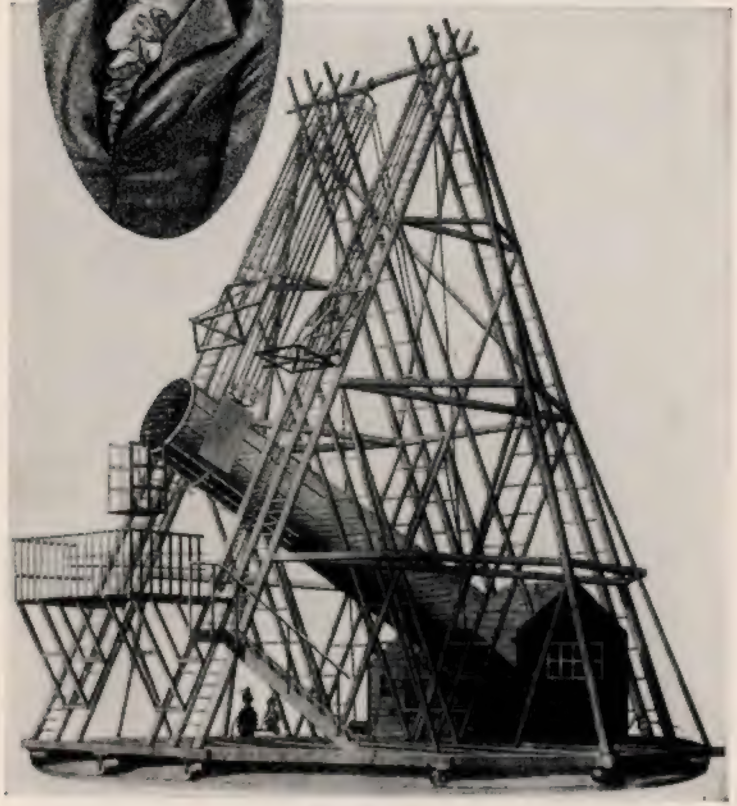
[PLATE 8]

Lick Observatory

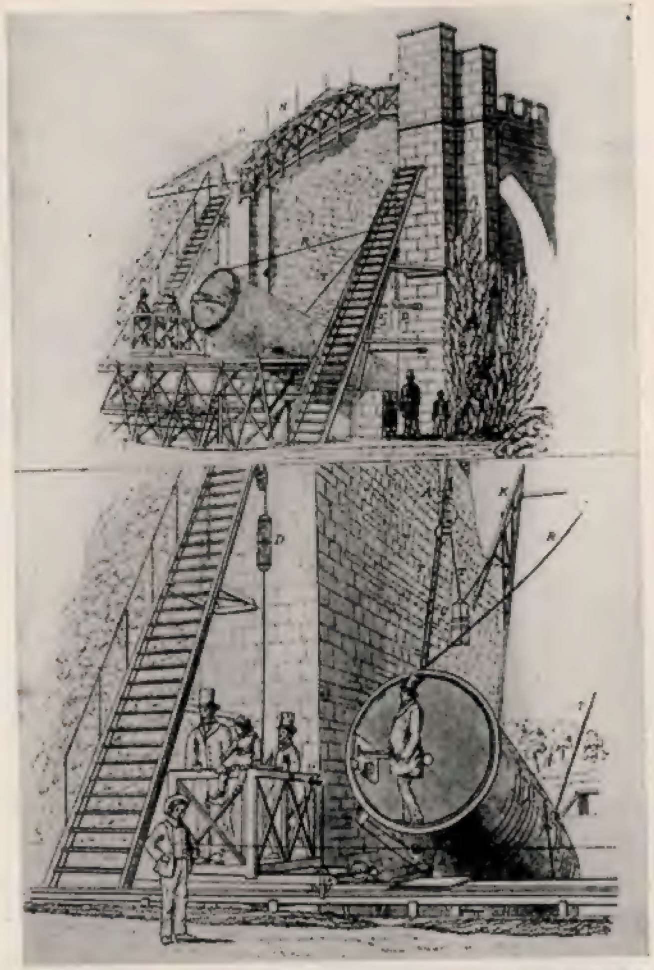
HALLEY'S COMET AS IT APPEARED AT ITS VISIT IN 1910
Photographed with a 6-inch portrait lens of 30 inches focal length at the Lick Observatory Station at Santiago, Chile

[PLATE 9]

WILLIAM HERSCHEL AND HIS 48-INCH REFLECTING TELESCOPE



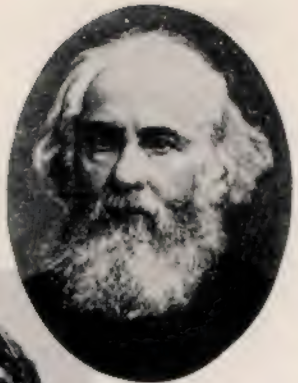
[PLATE 10]

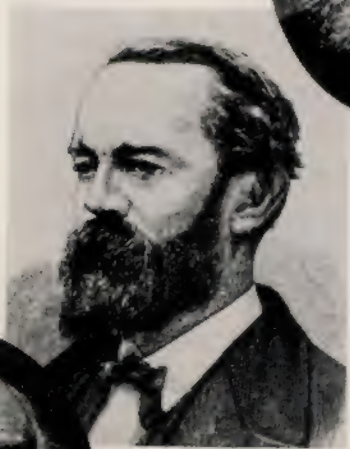


LORD ROSSE'S GREAT 6-FOOT REFLECTING TELESCOPE
Two views of the last of the speculum-metal giants

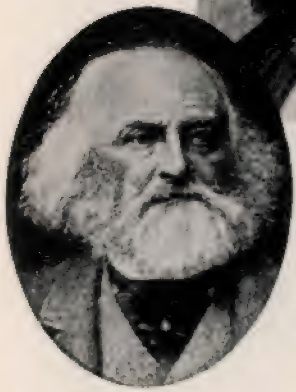
[PLATE 11]

SIR WILLIAM HUGGINS





DR. HENRY DRAPER



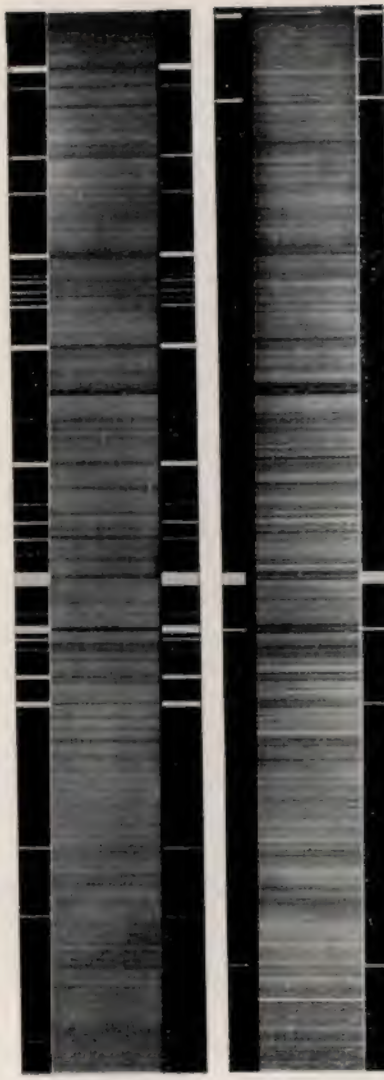
DR. LEWIS MORRIS RUTHERFURD

[PLATE 12]

Yerkes Observatory

HOW THE SPECTROSCOPE REVEALS THE COMPOSITION OF A STAR

Spectrum of Arcturus compared with spectrum of the element Titanium. Bright lines of Titanium exactly match dark lines in the spectrum, proving the existence of this element in the outer envelope of the star



Yerkes Observatory

HOW THE SPECTROSCOPE SHOWS MOTION IN A DOUBLE STAR

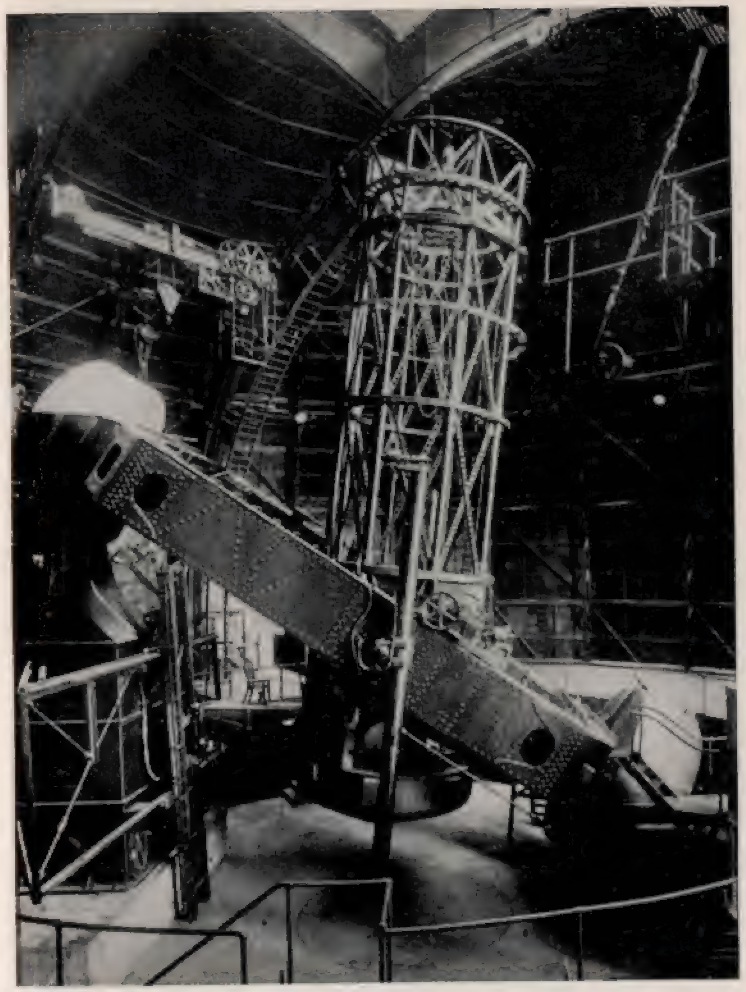
The star lines are single in the upper spectrum, indicating that the components are moving at right angles to the line of sight. In the lower spectrum the lines are double, indicating that the components are moving in opposite directions in the line of sight. These are spectra of the double star Mizar

[PLATE 13]

Yerkes Observatory

THE 40-INCH REFRACTING TELESCOPE AT YERKES OBSERVATORY. WORLD'S LARGEST REFRACTOR

[PLATE 14]



Mt. Wilson Observatory

THE 100-INCH REFLECTING TELESCOPE OF THE MT. WILSON OBSERVATORY

[PLATE 15]

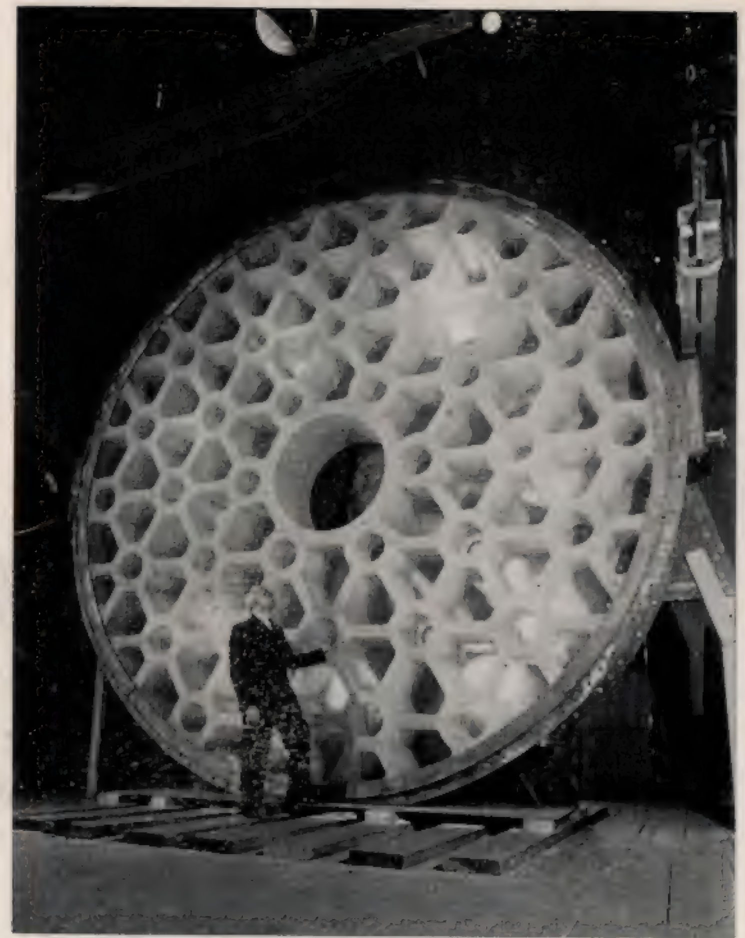


Photo by Robert Yarnall Ritchie, Courtesy Corning Glass Company

GRID-WORK OF GLASS

Back view of the mirror disc of the 200-inch telescope as it appeared upon removal from its annealing oven at the Corning Glass Works. The honeycomb structure reduces the total weight, at the same time providing rigid reenforcement for the mirror

[PLATE 16]

VI

Meanwhile the telescope was steadily undergoing improvements of a less spectacular sort, and some of these quiet and unobtrusive changes and devices were destined to become incorporated in the best instruments of later periods, whereas the feature of length was at most a transitory matter.

As early as 1638 William Gascoigne, a young Yorkshireman who later died fighting on the side of the King at the battle of Marston Moor in the Great Rebellion of 1644, made the capital discovery that any object placed in the main focus of the Keplerian telescope would be magnified by the eyepiece, along with the image.

It follows from this that a very fine thread, such as the thinnest silk or the web of a spider, introduced properly into the field, can be used for measuring directly the angle between two close objects, or the diameter of such bodies as the moon and planets. Moreover, by crossing the hairs at the exact center of the field, a most exquisitely accurate guide may be established for determining the exact instant at which a given star passes the meridian.

Gascoigne thus invented, in his short life, both the *filar micrometer* used today in accurate visual measurements of angular distance, and the cross-hairs which provide the closest possible modern measurement of time. Only the photographic plate, which is a relatively recent invention, provides a more precise measure of angular separation between two celestial bodies than the filar micrometer, yet this precious discovery of Gascoigne's, for the sake of a forgotten war, was all but lost. It was not in fact rediscovered and adapted to large instruments until 1667 by the telescope-maker Adrien Azout in Paris.

About the same year another French astronomer, Jean Picard, applied Gascoigne's invention of the cross-hairs to telescopes used for sighting, and adapted the principle also to the sights of the large sextants and quadrants still in use at that time for astronomical measurement. Presently "telescopic sights" had been placed on practically every large active sextant and quad-

rant in Europe, with the single and notable exception of those employed by Hevelius. This doughty astronomer, despite friendly and sometimes even acrimonious criticism, clung to his old reliable non-telescopic sights, and was able in the end to humble his critics by making observations that agreed with the best obtained with the aid of the new-fangled device. That, however, was because of Hevelius' sharp, well-trained eyes, and not through any fault in the invention of William Gascoigne.

FIG. 12

Scheme of the Huygens Eyepiece. The foremost lens of the eyepiece pair focuses through the second into the eye.

A second improvement which has altered the design of the telescope even to our time was the invention, by Christiaan Huygens, of the eyepiece which bears his name (Fig. 12). The Huygens eyepiece is based on the principle of the Keplerian eyepiece, but instead of one double convex lens it consists of two, plano-convex and differing slightly in diameter and focal length.

The value of this type of eyepiece is in the clear, wide field it provides—nearly four-fold larger than in the simple Keplerian telescope. Also—and this is important—it is substantially achromatic; that is, it compensates itself for chromatic aberration. It is widely used today not only on telescopes but also in microscopes, where the eyepiece problem is essentially the same.

VII

But what about spherical and chromatic aberration where they cause most damage—in the objective?

As to the possibility of overcoming them there had grown up two schools of thought. One held that the aberrations could be eliminated by proper curvatures and proper selection of different materials for the lenses. Adherents of this school often argued from analogy, holding that the human eye is an example of an optical instrument having neither spherical nor

chromatic aberration. Tho this was a mistaken argument, it nevertheless led to important results, as we shall see.

The other group clung to the belief that while spherical aberration could be avoided were it possible to give the lens a hyperboloidal figure, chromatic aberration could never be overcome. Presently this notion was bolstered up by a classical error made by Isaac Newton. Through a single hasty and ill-considered experiment Newton came to the astounding conclusion, now known to be false, that *refraction,* or the bending of light, and *dispersion,* or the separation of the colors, are exactly proportional in all substances. Therefore no lens, no matter what its shape or what the material of which it is made, can be free from chromatic aberration!

It was a bungle that was to delay the coming of achromatic telescopes for more than seventy-five years, for the word of Sir Isaac Newton in such matters was beyond question in the latter part of the seventeenth and the early part of the eighteenth centuries. What is more, Newton seems to have felt that of the two evils inherent in contemporary telescope design, chromatic aberration, which had not troubled Descartes at all, was the chief. He accordingly gave up the refracting telescope as lost, and cast about for a substitute—some other type of instrument that would make it possible to see at a distance, but which should not be plagued with aberrations of any kind.

Now it happens that in 1663 James Gregory, a prominent Scottish mathematician, had published a drawing and description of a proposed instrument endowed with just those characteristics. It was a telescope that made use of a concave mirror instead of a lens. Gregory had shown it in his cross-sectional drawing as a paraboloidal mirror, so arranged as to bring the rays to a focus at a point above the center. Just inside this focus on his drawing the mathematician had inserted a second con-

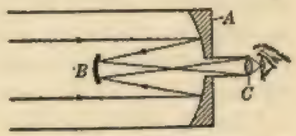


FIG. 13

Gregory's Reflecting Telescope. Light entering in parallel rays is focused by the large concave mirror A, and passed out of the telescope by the small concave mirror B to the eyepiece C.

cave mirror, much smaller, which cast the converging rays downward again and passed them out of the telescope through a hole in the center of the large mirror (Fig. 13).

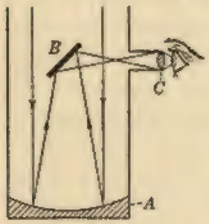


FIG. 14
Newton's Reflecting Telescope. Parallel rays of light are focused by the large concave mirror A, and passed out the side of the telescope by the plane mirror B to the eyepiece C.

Such a contrivance would have practically no aberration, provided the curvatures were as Gregory had suggested. Since the light does not pass through glass (except in the eyepiece), there can be no dispersion. And if the great mirror is a paraboloid, and the smaller one elliptical, no sensible distortion of the image due to the reaction of light to a spherical surface will appear.

But alas for Gregory's telescope! No man living in 1663 could produce mirrors with the exquisite curvatures required. The mathematician commissioned Reive, one of the foremost opticians in London, to try the manufacture of such a telescope. After struggling with the problem for several months the Londoner was obliged to give it up as a bad job. Even the clever scientist Robert Hooke, who had been able to make a number of kinds of instruments work when others had failed, was unable to construct a useful Gregorian reflector, tho he tried in 1674.

Newton, examining Gregory's drawing, concluded that the chief trouble with the Scotsman's telescope was the requirement of two curved mirrors, both difficult to make. Accordingly he drew up plans for a simpler type, in which the converging rays from the great mirror would be passed out the *side* of the telescope by a small plane mirror (Fig. 14).

Newton built the first such telescope himself in 1668, employing for his main mirror or speculum the white, brittle metal often used in making schoolbells. He made a second in 1671, and presented it to the Royal Society in December of that year, just before his election as a Fellow.

The second Newtonian reflector is still in the possession of the society. It is in reality only a model, with a focal length

of six inches, and stands about fifteen inches high (Plate 8). Neither of Newton's telescopes was of any particular use as an astronomical instrument, probably because he insisted that the curvature of the speculum should be spherical, whereas in fact it should have been paraboloidal, like the curve of the reflector of an automobile headlamp.

To Gregory's and Newton's suggestions for reflecting telescopes another was soon added. The French sculptor Sieur Guillaume Cassegrain, an artist of note who dabbled in astronomy as an avocation, contributed the third design to science in 1672. Cassegrain's reflector bears a family resemblance to Gregory's, except that instead of a concave small mirror it provided one that was convex. With properly shaped mirrors (neither spherical) this type turned out to have many special advantages, particularly the great focal length possible with a relatively short tube. Most large reflectors of today are arranged to be used either in the Newtonian or Cassegrain forms.

But that was a matter of later development. In 1672, and indeed for half a century thereafter, the reflecting telescope was nothing but a laboratory curiosity. The difficulty, not to say impossibility, of giving the mirrors proper figure precluded the construction of any such instrument for astronomical use.

Chapter V

ASTRONOMY'S ADVANCES GO HAND IN HAND WITH IMPROVEMENT IN TELESCOPES

I

IT must not be thought that the advancing science of astronomy was standing still while zealous telescope-makers vied with each other to see who could construct the longest, most unwieldy instrument, or suggest the newest thing in reflectors. Besides these relatively useless monstrosities, the world was well equipped in this period with excellent refracting telescopes of shorter focal length; troubled with spherical and chromatic aberration, to be sure, but not enough to impede the progress of science. Also, the introduction of better methods of making lenses—due to Huygens—and the invention of the micrometer and improved eyepiece, made telescopes more useful than ever; sufficiently so to reveal vast new reaches of the planetary system and many of its oddities and wonders.

The period from about 1625 to 1775 was one of great advances. In this era the groundwork of modern astronomy was laid, carrying on the work of Kepler, Galileo and Huygens through the contributions of Flamsteed, Cassini, Newton, Halley, Bradley, Roemer—giants of astronomy whose names are still of magical import.

The honeymoon period of effortless discovery with the telescope was past. The future was to the man with good instruments, who could observe carefully; who moreover could use his head and the growing science of mathematics in interpreting what he saw. It was the beginning of the era of exactness, when men perceived that the greatest significance might attach to the smallest fraction of variation in things observed; when

approximate results and observations were no longer good enough.

II

There was, for example, the matter of the size of the solar system. It follows from Kepler's famous laws of planetary motion that the *relative* dimensions of the system—the distance of all the planets from the sun in terms of the sun-earth distance—can be determined accurately by mathematics. But to translate those relative distances into miles requires the exact determination of an angle called the sun's *parallax*. This is one-half the angle represented by C in Fig. 17. It is equal to the angle at the apex of a long triangle, of which the base is the radius of the earth and the tip the center of the sun; in other words, the angle ACD of the same figure.

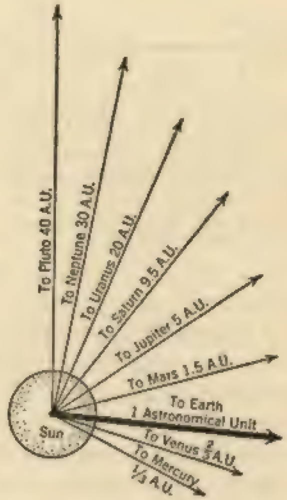


FIG. 15

Finding the Dimensions of the Solar System. From Kepler's laws the distance of the planets from the sun may be calculated in terms of the earth-sun distance, or *astronomical unit.* If the length in miles of the astronomical unit can be discovered, the numerical size of the solar system will be revealed.

When this angle has been determined, trigonometry provides a simple way to reduce the *astronomical unit*—the sun-earth distance—to miles or any other unit of measurement required. And since the relative distances of the planets from the sun are already known, these, too, can then be obtained in miles and the true dimensions of the solar system revealed (Fig. 15).

Theoretically the parallax of the sun may be learned by direct measurement, applying the simple method used by surveyors when they wish to measure the distance of a far-off

object, such as a mountain peak. The procedure is to lay off a base-line from camp, at right-angles to the line of sight on the mountain. With instruments the angle to the peak from each end of this base-line is then determined, from which the third angle, at the mountain, readily can be obtained by plane geometry (Fig. 16).

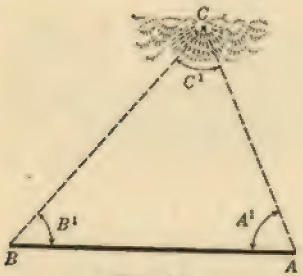


FIG. 16

Determining the Distance of an Object. The base-line AB and the angles A^1 and B^1 are found by measurement. The angle C^1 and the distances AC and BC can then be calculated.

A base-line of a few hundred yards will usually suffice for all measurements of objects on the earth, but when it comes to determining the parallax of the sun a much longer base-line will be needed, since the angle at C (Fig. 17) is so small that the slightest error will ruin the calculation. The longest base-line on the earth—its diameter—is in fact too small to provide this angle with accuracy, tho it can be used to determine the distance of the moon and the closer planets, Venus and Mars, when they are nearest to the earth.

In the year 1672, when Mars was in opposition—had approached as close to the earth as is possible—such an occasion presented itself. And in that year came the first scientific effort to determine the size of the solar system. It was, like so many surveys even to this day, a cooperative effort, covering half the world and participated in by an Italian, a Frenchman and an Englishman. These men were Giovanni Domenico Cassini, first of four generations of Cassinis to serve as director of the Observatory of Paris and an Italian who later became a naturalized Frenchman; the French astronomer Jean Richter, and John Flamsteed, three years later to become the first Astronomer Royal of England.

Now there are two direct ways by which the parallax of Mars can be learned. A single observer may get it by observing Mars' apparent change of position against the pattern of fixed stars

in two observations a few hours apart. Since, due to the rotation of the earth, the observer would meantime have moved eastward a distance equal to the amount of the earth's turning in that time (allowance being made, of course, for the earth's motion in her orbit) Mars' apparent shift of position as compared with the pattern of the skies beyond would be a function of that motion, and the apparent angle of the shift would reveal his parallax.

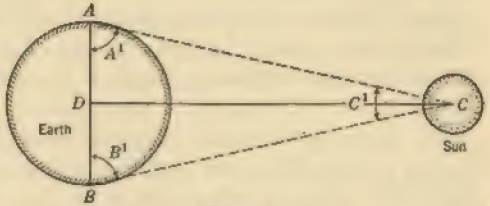


FIG. 17

Finding the Distance of the Sun or a Planet. Observers at A and B, widely separated points on the earth, simultaneously sight on the body, C, and measure the angles A^1 and B^1. The distance AB can then be determined, and with these data the angle C^1 and the distance from the center of the earth to the center of the body.

Another method would be for two astronomers to observe Mars simultaneously from widely separated points on the earth.

Measurements of the first kind are obviously best done at or near the equator; while those of the second require an appreciable part of the earth's circumference between the observers. Cassini, Flamsteed and Richter, in order to be doubly certain of their results, determined to make measurements by both methods. They sent Richter to Cayenne, in South America, from which point near the equator he made a number of observations of the planet at times and intervals carefully noted. Meanwhile Flamsteed in England, and Cassini with the remarkably good instruments he had assembled at the Observatory of Paris, were making observations from Europe.

When all the data had been obtained and computed by Cassini, the resulting figure for the sun's parallax showed a remarkable—almost unbelievable, thing. In the time of Tycho Brahe estimates of this angle arrived at by various methods indicated that it might be as much as 180 seconds of arc, a value so large as to bring the sun within about 4,000,000 miles of the earth.

Kepler had been dissatisfied with this guess, and had himself concluded that it ought to be nearer 60 seconds, pushing the sun back nearly four times as far. In 1639, basing his figure on an observation of part of the transit of the planet Venus across the face of the sun, a young English clergyman, Jeremiah Horrox, had dared to believe that the solar parallax is in actuality much smaller even than the guess of Kepler, and he placed it at 14 seconds of arc.

But now, as Cassini completed his intricate computations, he was astonished to see that the parallax of the sun, as derived from the refined measurements of the distance of Mars, was less than 10 seconds of arc; a result that would hurl the sun back from the earth more than 80,000,000 miles, and cast the orbits of the planets fully a third farther into space than even the estimate made by the daring young clergyman Horrox!

Nor was this the end of the matter. For several reasons Cassini and his associates were by no means satisfied that they had obtained the true dimensions of the solar system. This uncertainty led astronomers to cast about for a better way of measuring the important angle, and drew a great deal of attention to the method suggested about 1691 by the young astronomer Edmund Halley, who thirty years later was to succeed Flamsteed as Astronomer Royal.

Halley, studying the report made by Horrox regarding the first observed transit of Venus, pointed out that careful observation of the transit of this planet, another of which was due to occur on June 6, 1761, would provide a means of determining the solar parallax with a probable error of less than a 500th of its true value; accuracy sufficiently fine to settle once and for all the magnitude of this fundamental constant.

It was, indeed, to prove a useful measurement, but the world-wide observation of the transit of Venus in 1761 is another story and must be reserved for the end of this chapter, coming as it did toward the close of a century notable for progress in astronomy.

III

We must turn our attention now to the founding of two great national observatories: the Observatory of Paris in 1667 and the Royal Observatory at Greenwich, England, in 1675, and the curious manner in which both of these institutions, almost in their first years, contributed to the development and completion of Newton's theory of gravitation.

As befits the British temperament, the Observatory at Greenwich was dedicated to usefulness from its opening days, bound to a definite program and controlled by the stern and inflexible will of John Flamsteed. It was the purpose of the Royal Observatory to aid navigation, to help in the task of maintaining His Majesty's navy in its supremacy of the seas, and to give aid to the ever-enlarging merchant fleets of Britain as they reached out to the farthest shores for trade.

Hence, very soon data on the motions of the moon and planets began to be accumulated there which surpassed anything ever before available.

The Observatory of Paris, on the other hand, was operated on quite a different plan. From the beginning it had no such ambitious program; its instruments were not restricted to the uses of "practical" observation, but rather were free for all kinds of astronomical research—whatever should come into the head of the astronomer at the eyepiece. It was, in fact, more like an astronomical club than a modern observatory—just the kind of observatory that would have delighted the heart of old Hevelius, and in the beginning much like the one he had imagined in his *Machina Celestis*.

Soon after the ornate main building was finished in 1671 (it was designed as a great monumental piece by the architect Claude Perrault), Cassini went to Rome and brought back with him a telescope of 17-foot focus which was among the finest in Europe, the work of the telescope-maker G. Campani. Later he added to this collection several other long telescopes by the same maker, including one of 34-foot focus and another of 100 feet.

With these he began his notable investigations of the planet Saturn. It will be remembered that Christiaan Huygens had already discovered one of the satellites of Saturn and explained the nature of the ring with which this phenomenal planet is belted. In 1671, Cassini discovered with his 17-foot glass another satellite, the moon Iapetus. The following year he saw another of this numerous family of moons, Rhea, with the Campani 34-foot telescope. He then found, in 1675, the most remarkable phenomenon of all—the dividing line between the rings, which Cassini was first to observe, and which today bears his name.

With the 100-foot telescope he then discovered two other satellites of Saturn, showing that this planet, largest but one in the solar system, not only had two splendid rings, but a family of at least five moons. (Saturn is now known to have ten, but five are too small to have been seen by instruments then available to Cassini.)

Gathered around this astronomer in his Paris Observatory was a group including some of the finest observers of the time. Among them were Olaus Roemer, of whom we shall hear more presently, and Jean Picard. It was Picard's remarkably accurate measurement of the earth—or more exactly the length of a minute of latitude on the earth's surface in northern France—that gave Newton the final keystone to the arch of gravitational theory he had been building for many years, and was the unique contribution of the Paris Observatory group to this great theory.

Newton first began—as early as 1666, when he was only twenty-four years old—to consider whether the earth's gravitation might not be a clue to the mystery of planetary motions. Indeed, the idea in this stage was not particularly original with him. Even Copernicus, in his *De Revolutionibus,* entered into some speculation as to whether all celestial bodies are not endowed with gravitation. Jeremiah Horrox had some interesting theories about gravitation prior to 1639, and began a study of tidal action in the last months of his life with the notion of determining whether these familiar risings and fallings of the water might not be due to the attraction of the moon.

Later the idea came independently to several of Newton's contemporaries, including the astronomer Robert Hooke, the architect Sir Christopher Wren, and to Edmund Halley. But it was Newton who first put it in clear, concrete form, and who, moreover, produced such proof that his theory of gravitation was completely incontrovertible.

That proof rested upon careful and accurate observational data. John Flamsteed, finest observer of planetary motions in all England, had gathered a veritable treasure-house of such information, which was made available to Newton. But still the great theory of gravitation, which asserts that all objects in the universe attract each other inversely as the square of their distance and in proportion to the product of their masses, failed to predict the observed motion of the object nearest to the earth—the moon.

For Newton had concluded that if gravitation were the force that shaped the orbit of the moon, then that body was continually in free fall toward the earth—the direction of the fall however being a resultant between the moon's forward or tangential speed and the velocity of its fall (Fig. 18). Now, to fit observed facts, this resultant should be such as to cause the moon to follow an elliptical path around the earth—a path of curvature just right to bring the moon back to its

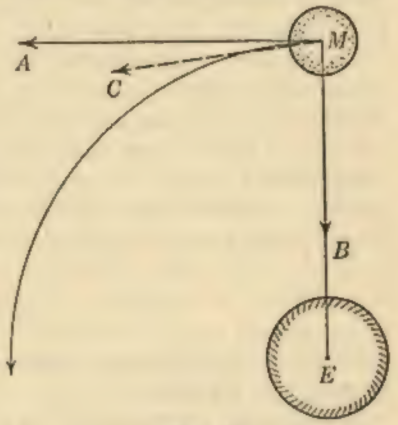


Fig. 18

How Gravitation and Centrifugal Force Cause a Body to Pursue a Curved Path. The earth E pulls the moon in the direction B, while the moon's velocity in its orbit tends to send it in the tangential direction A. The resulting actual path is a compromise between the two, represented by C. As the moon moves into the new path the tangential and gravitational forces continue to act on it, producing a continuously curved orbit around the earth.

starting point after each cycle had been completed. What Newton actually found, when he completed his computations, was that the theory as he had outlined it failed to account for the observed path of the moon by about 16 per cent.

This wide discrepancy was fatal to the theory; obviously something was wrong, and Newton turned to other things until the flaw in his reasoning should become clear to him. In 1682, sixteen years after he had first begun working out the theory, the answer came. In that year Newton's attention was called to Picard's remeasurement of the earth. Prior to Picard's work the distance represented by one degree of latitude in northern France had been considered to be approximately 60 miles. Picard's remeasurement had shown that the true distance was a little more than 69 miles—a difference of not quite 16 per cent!

As the story goes, Newton instantly saw that the new figure would wipe out the discrepancy in his calculation; he had all the time been figuring on too small an earth. So great was his excitement that he was unable to make the simple arithmetical computations needed to confirm this surmise. Tho he was the greatest mathematician in the world, he was obliged to call in an assistant to make the calculation for him!

IV

Now for Olaus Roemer, whose imagination tricked light into revealing its velocity.

Roemer was interested in the little moons of Jupiter, those same little moons that Galileo first observed when he directed his telescope into the heavens. But, unlike Galileo, Roemer was not interested in discovering more moons, or even in learning anything more, especially, about those already known. He was working on a problem far more abstract and supremely more important. He was wondering whether those little moons of Jupiter, with their short periods of revolution around the giant planet, could not be made to help him discover the speed of light.

Roemer was not only an expert observer of the planets himself, but a man who had a genius for mechanics. He is credited with having invented, in the Paris Observatory, an altazimuth mounting for telescopes in 1678, and a parallactic or equatorial mount operated by clock-work in such a way that a telescope carried on it could follow the daily motion of the stars. Whether he actually invented these additions to Cassini's equipment is somewhat in doubt, but he certainly did construct a transit instrument, by which time could be checked up more accurately through observations of the crossing of stars over the meridian. To him is also attributed the type of telescope afterward used by Bradley in his studies of the movements of the stars—an instrument that could never be pointed any direction but straight up, but which would, in this position, show with extreme accuracy any deviation in the repeated transit of a particular star.

In pondering the problem of the little moons of Jupiter his particular genius for mechanics—for what might be called "celestial mechanics," tho in a different sense from that implied by this term today—again showed itself.

The idea that light has a definite speed, for all that it seems to ordinary mortals to be instantaneous in its travels, was not new with Roemer. There were already some very good theories of light in existence. Huygens, explaining why light acts as it does in connection with lenses, had developed a rudimentary wave theory, and common sense shows that waves cannot travel from place to place instantaneously, tho they might go very fast at that. There was also the alternative theory advanced by Newton, that light consists not of waves, but of streams of infinitely small particles traveling at high speeds from the source—light-bullets so infinitesimally tiny that they can pierce through glass without leaving holes. Under either theory, it was clear that light must have a finite speed. What this might be was the problem which Roemer set himself to solve.

Now Jupiter's inmost satellite revolves around that giant globe at a tremendous rate—so fast that it makes the entire circuit in about 42½ hours. The exact instant at which it passes behind Jupiter may be determined with any good telescope, likewise the exact instant at which it reappears. But the disappear-

ance and reappearance are signaled to us only by the agency of light. Hence, if there is any difference in the apparent time in which the satellite reappears during a period in which the earth is greatly increasing its distance from Jupiter by movement in its orbit around the sun, that difference must represent the length of time required by light to cross from the point where the earth stood at the earlier observation to its position at the latter one (Fig. 19).

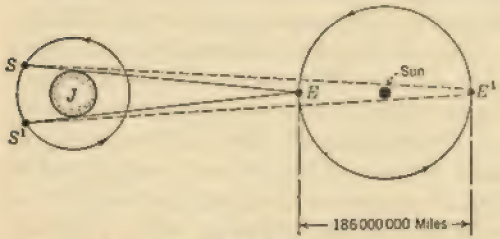


FIG. 19

How Roemer Measured the Speed of Light. The satellite S of Jupiter seems to disappear behind the planet at S earlier, and reappear at S¹ earlier, when viewed from E, position of the earth at the near side of its orbit, than at E¹. The difference is a measure of the time required for light to cross the earth's orbit.

Roemer began by timing the reappearance of the satellite on successive occasions, but soon found that the difference in time at 42½-hour intervals, tho perceptible, was too small to measure, despite the fact that the earth moves approximately 18 miles a second in its orbit, and in 42 hours changes the distance between itself and Jupiter by nearly two and three-quarters million miles!

But, nevertheless, there was a difference. Roemer, persisting, soon saw that what was an almost imperceptible increase in time in a few revolutions of the satellite became a sizable amount as the earth progressed around its orbit from the point nearest Jupiter to the opposite side, more than 180,000,000 miles farther away.

The difference this change in distance produced, as measured by Roemer, was nearly 22 minutes of time. Twenty-two minutes for light to travel across the diameter of the earth's orbit! From this it would follow that light travels at the tremendous, unbelievable speed of nearly 150,000 miles a second!

We now know, thanks to more refined measurements, that light actually travels faster than this—more than 186,000 miles a second—that it traverses the earth's orbit in about 16 minutes 37 seconds. But what a triumph for Roemer that he should have been able to come so close, with the aid only of Cassini's long, thin telescopes, a clock, and the inner satellite of Jupiter!

V

While exploits such as these were afoot in France, and the Observatory of Paris was becoming famous for its brilliant men, its marvelous telescopes and its astonishing discoveries; equally important things were being brought to light across the English Channel.

Among the foremost British astronomers of the day was Edmund Halley, famous son of an obscure soap boiler, later to become the second Astronomer Royal of England. Halley was known in his day for his geniality, his good manners, the richness and versatility of his mind, and the enthusiasm with which he approached science in all its phases, casting out brilliant ideas like sparks from a grindstone. Today he is still remembered as a great man, if for nothing more than his charting of the orbits of more than a score of comets, including that of the huge and regular visitor to the neighborhood of the sun which is known by his name.

Until Halley's day comets were among the most mysterious of the heavenly bodies, and had been held to presage catastrophe for so long that even the foremost astronomers considered them special apparitions, probably not governed by the ordinary laws that controlled the movements of the other celestial entities. Tho sensible people no longer take stock in the ancient notion that stars and planets by their configurations foretell events to happen on earth, the first sight of one of these flaming swords of the sky is enough to strike terror into the heart even today. No wonder they were in old times coupled with prophecies of pestilence, war, flood, famine and nameless dread!

Tycho Brahe had made a study of comets, and boasted that

he was first to prove them celestial visitors and not disturbances of the earth's atmosphere, as some before him had believed. He proved, moreover, that they come toward the sun from long distances, cutting through the imagined "spheres" of Ptolemy, therefore showing that those spheres cannot consist of solid materials such as glass or crystal.

Kepler and many other astronomers after Brahe considered comets of relatively little importance as objects for study, being as they thought ephemeral visitations, either thrown out from the sun or moving like luminous wisps of cloud through the firmament until they disintegrated and disappeared of their own accord, never to return.

Halley himself was at first of the opinion that comets follow a parabolic orbit, and tho coming in toward the sun at tremendous speed, are hurled outward so fast by the sling-shot force of this passage that they never return to the vicinity of the solar system, but drift forever outward into the darkness of space. But when he came to examine the great number of comets that had been recorded by astronomers from the times of antiquity, he was struck with the enormous swarms of these visitors in space that would be required to exist under the theory that an individual comet, once swinging into our system, never returns.

He then studied carefully the paths of comets, and plotted the orbits of twenty-four. This work revealed the startling fact that the course of a comet is not a parabola, as he had supposed, but an ellipse—in short the same kind of course as that traveled by the planets, except that the paths of the comets are tremendously elongated, whereas those of the planets are so pulled in at the ends that, tho still ellipses, they are very nearly circular.

The only conclusion that may be drawn from this astonishing discovery is that comets, like planets, are slaves of the sun. Tho they may fly outward millions, perhaps billions of miles into space, nevertheless they must always return again to that fiery star upon which they, like the planets, depend for light.

This led Halley to make a prediction, one of the two famous ones he made which could not be fulfilled until after his death,

but which came about exactly as he had forecast. He predicted that the great comet which he had observed in the year 1682—most spectacular and largest of all the "bearded stars," would return again. Looking back through the records, he found indications that a comet answering the same general description had appeared before at intervals of 76 years (we now know that it was seen and recorded by Chinese astronomers for hundreds of years before the time of Christ). He therefore made the daring prediction that it would return in the year 1758, which it did.

It has continued to reappear at the same interval (with slight variations due to gravitational interference from the large planets near which it passes) ever since. Halley's comet was last seen in May, 1910 (Plate 9). Unless something happens to it in its present cold journey outward into the interstellar spaces, it will again be observed, by many persons now living, in the year 1986.

Halley's second prediction was that Venus would effect her transit across the face of the sun on the morning of May 26, 1761, at which time he believed astronomers should be on the lookout for the phenomenon, for it would provide them with an accurate means of determining the parallax of the sun within closer limits than had been possible to Cassini, Flamsteed and Richter at the opposition of Mars in 1672.

To these contributions Halley added another in 1718, when, by comparing ancient star charts with those of his own time, he discovered that three huge stars, Arcturus, Sirius and Palilicum, had moved from the positions assigned them. Since the ancient locations were confirmed by three independent investigators, Halley could only conclude that they had indeed moved; that the "fixed stars" which for countless generations had seemed to act always in unison, had "proper motions" of their own.

This, of course, is true for all the stars; it goes without saying in the modern theories of the mechanics of the universe, but in Halley's time it was the most startling discovery of all, and one to make men wonder whether the universe, seemingly so solid and unchanging, was really enduring, safe and secure. For

if stars can move, can they not also collide? And if other stars move, may not the sun and his family of planets also be winging through space in some unknown direction? And finally, what is to guarantee that all these apparently random movements will not result in such a catastrophe as to wipe out the world and its helpless inhabitants? These are questions which may well be asked even today.

VI

Now we must consider the activities of a man who went down into a cellar to view the stars, and from this curious vantage point proved that the earth revolves around the sun.

He was James Bradley, a Gloucestershire clergyman and a very patient man. He did his work with an extraordinary telescope erected for his observations by his friend Samuel Molyneux in an old house at Kew.

The idea of this telescope was not original with Bradley or Molyneux, but came to them from the same Robert Hooke who is so often mentioned in the history of science of those stirring times.

Hooke had conceived the idea (possibly at the suggestion of Roemer) of making an instrument that was anchored in one position only—directly toward the zenith. Such a telescope would be of no use whatever in observing planets, comets or moons, but would be extraordinarily valuable in determining the variations in the position of a single bright star, by recording that position with great exactness every night as it passed the precise zenith of the place of observation. By fixing the telescope so that it would have relatively little movement (only so much as would be needed to focus it on the star under consideration) and by checking up on its position at each observation by a true vertical line established with a plumb-bob, the tiniest variations would be revealed in the course of a year or so—variations which with any other type of telescope would be either too small to be detected, or too minute to be distinguished from motions attributable to the changing adjustment of the instrument.

Hooke thought such a telescope would be useful—might even reveal, for the first time in all history, the distance of a star through determination of its parallax.

Now, the parallax of a star is not quite the same thing as the parallax of the sun or a planet. It is the apex angle of a long triangle of which the center of the star is the apex and the radius of the earth's *orbit* the base (Fig. 20). The radius of the earth, which constitutes a base-line sufficient for determination of the parallax of Mars, is hopelessly inadequate for that of a star. So, for that matter, is the radius or diameter of the earth's orbit, lacking instruments much more precise than any Hooke was able to make. But he did not, of course, realize it; nobody would have believed then that the stars could be so far away that light would require more than four years to traverse the interval separating the earth from even the closest of them.

Hooke concluded that for his new instrument he would need a long telescope. But how could such an instrument be fixed in one position for a lengthy period without encountering variations due to vibration, winds, and other causes?

He hit upon a brilliant solution. He cut an opening through the roof of his house and fixed a square tube in it. In the floor directly below he cut a second hole, and through these two holes he placed the tube of his telescope, one of 36-foot focal length. Thus he caused the entire frame of the stanch old English house to become part of the supporting structure of his telescope. He attached a plumb-line with which its vertical setting could be compared, and the telescope was finished by fixing

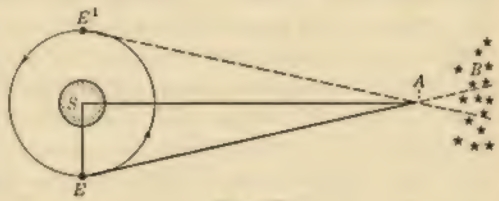


FIG. 20

Determining the Distance of a Star. The astronomer on the earth at E observes the position of the star A with relation to its more distant background B. Six months later, when the earth is at E^1, he again takes the observation. From the apparent shift in the position of A he calculates the star's parallax, which is the angle SAE. The distance SA can then be determined.

up cross-hairs and a micrometer at the principal focus, so that when a star under observation crossed over the zenith the moment could be determined with the greatest accuracy.

For all the ingenuity and labor that went into this interesting instrument, little seems to have come of it. Hooke lacked the patience needed to check up the passage of the star with sufficient regularity.

Bradley and Molyneux assumed that Hooke's failure was due to some defect in his instrument or his methods, and set about to construct a vertical telescope in Molyneux's house at Kew, in Surrey,—a telescope so perfect that there could not possibly be any failure this time.

The instrument was not quite as long as Hooke's; the focal length of the object-glass was exactly 24 feet 3.15 inches, and the focal length of the eyepiece 4½ inches. The telescope, while its objective was a little more than 4 inches in diameter, had a total effective diameter or "clear aperture" of 3.8 inches, and was placed in a metal tube 4 inches in diameter, blackened inside to absorb stray light.

This tube, in turn, was mounted in a square wooden tube 9 inches on a side, which passed through large holes in all floors of the house from the first to the roof. At its upper end it was fastened to iron-work secured to a pair of ancient, solid stone chimneys. With the greatest care a long plumb-line was then affixed at the upper end—a line so sensitive to the slightest vibration that it had to be "damped" in a small tank of water to keep it from swinging interminably. Cross-hairs of the finest silver wire were set in the focus of the object glass, and illuminated by a special lamp and shutter device which would light the cross-hairs as brightly as was needed to make sure that they were being seen clearly.

The whole telescope was swung from brasswork fastened to the iron braces at the top, in such a way that it could be moved a few degrees in a north and south direction; thus the movement of the star could be determined by the amount the telescope had to be moved to follow it. Since the pivot was at the upper end, and the calibrating devices at the lower, the

smallest movement of the star would be greatly amplified by the lever-like motion of the instrument.

It is unnecessary to repeat here the long series of trials and tests to which this unique telescope was put by Bradley and Molyneux before they judged it sufficiently accurate for their most exact requirements. About the end of November, 1725, the instrument was considered ready for its important work. Bradley, lying on the couch which had been placed in the basement at the eyepiece of the instrument, watched on the evening of December 3 the first passage of the star they had elected to use in their observations.

This star was the bright one in the head of the constellation Draco known as *Gamma Draconis*. As it passed over the zenith at Kew that clear December night Bradley checked its position. Like observations were made on the 5th, 11th and 12th of the same month, and there being no observable difference in position Bradley did not return to the instrument again until the 17th. Then, having adjusted the telescope in the usual way, he perceived that the star passed a little more to the south than it had been observed to do before.

This was an astounding and inexplicable discovery, for at that time the earth was moving in its orbit in such a way that, had the observed movement been due to the star's parallax, it would have been toward the *north*. Bradley and Molyneux, thinking that the result was caused by some fault in their instrument or a trick of the eye or atmosphere, observed again on December 20. The star now passed *a little more southerly* than in former observations. All winter the star continued to go toward the south—in short, to *follow the earth's movement* around the sun. By the beginning of March, 1726, it was found to be 20 seconds farther south than at the time of the first observation.

But now it had reached its southernmost point, and remained there for a few days. By the middle of April it appeared definitely to be turning toward the north. About the beginning of June it passed at the same distance from the zenith as it had done the preceding December.

From the quick alteration in its declination at this time (it moved as much as a second in three days) Bradley and Molyneux concluded that it would continue northward until the following September, then swing back toward the south. This prediction proved accurate. By the first of December, 1726, the bright star *Gamma Draconis* was in the position from which it had started, having made a swing north and south across the zenith of no less than 39 seconds of arc in the course of the year!

This clearly was not the parallax that the astronomers were looking for. But how account for it? Bradley and Molyneux checked over every possible point of error in their instrument. The telescope had not slipped in any of its adjustments; the chimneys had not given by even the smallest fraction of a second of arc; the plumb-line showed true. Everything was seemingly in order throughout. Besides, Bradley had long since set up another zenith telescope in a house at Wansted, some distance away—a telescope that differed from that at Kew only in that it had more movement in latitude and permitted the astronomer to observe the behavior of other stars near the zenith.

He found that all the stars visible in this instrument performed the same north-south annual swing. Moreover, by clocking their times of crossing the zenith he perceived that it was not a north-south movement only, but a circular one. The stars nearest the pole described nearly perfect circles; those lying between the pole and the zenith toward the north ellipses, and only the stars overhead made a direct north-south line. In every case, however, the amount of motion was about the same—a diametrical displacement of nearly 40 seconds of arc.

Bradley considered whether the change could have been due to refraction, but finally ruled this out, together with the hypothesis that the stars themselves had moved. An effect so closely coinciding with the annual period of the earth must certainly be a phenomenon connected with the earth's revolution around the sun.

The true explanation occurred to the astronomer while he was taking a sail on the Thames. He noticed that when the boat veered in its course, as it did from time to time, the little flag at the top of the mast did not follow but flew independently, and nevertheless obviously did not show the true direction of the wind. He asked a sailor to explain this phenomenon, and the sailor pointed out that the flag indicated neither the direction of the boat nor the true direction of the wind, but a resultant of the two. If the boat were going at right angles to the wind, for instance, and at the same speed as the wind, the flag would show an angle of forty-five degrees to both.

Then the thought came to Bradley that if the earth were moving at high velocity around the sun, and light were coming at fixed rate of speed from a star, the effect of the conjunction of these two velocities would be to make the star seem to be in a somewhat different position from its true place. It is a phenomenon similar to the common experience of walking through a vertical rain with an umbrella. If one stands perfectly still under the umbrella, none of the drops can reach him; but if he moves, the rain will seem no longer to be falling vertically, but will come in under the umbrella from the front.

"For I perceived," said Bradley, "that if light was propagated in time, the apparent place of a fixed object would not be the same when the eye is at rest as when it is moving in any other direction than the line passing through the eye and the object, and that when the eye is moving in different directions, the apparent place of the object will be different . . ."

So, while Bradley did not find the parallax of a star, from which he was forced to conclude that the stars are almost unimaginably distant ("It seems very probable that the parallax of *Gamma Draconis* is not so great as one single second; and consequently that it is above 400,000 times farther from us than the sun"), he nevertheless produced positive proof that the earth does move around the sun, a question which even in his day, 200 years after Copernicus had published his theory, was still seriously debated by persons to whom Bradley refers in his thesis as "Anti-Copernicans."

The phenomenon discovered by Bradley is known today as the *aberration of light*. It is a quantity greater than the

parallax of any star, and must always be taken into account in astronomical calculations that deal with the movements of stellar bodies.

VII

Bradley succeeded Halley as Astronomer Royal, and promptly upon taking up his duties at the Greenwich Observatory he fell to examining the instruments which Halley had used, and compiled a careful report of their condition, their inaccuracies, and the faulty practises of his predecessors. This report gives us an illuminating glimpse into the nature of the equipment with which the Observatory was then furnished, and incidentally into the personality of that great but perhaps too easy-going man, Edmund Halley.

"When I came to reside at the Observatory in June, 1742," wrote Bradley, "I made but few observations either with the mural quadrant or the transit instrument until I had made some alterations in both." For instance, there was no good method of illuminating the cross-wires of the telescopes, either of the quadrant or the transit instrument. Halley had been content to illuminate the wires of the quadrant by placing a candle on the south end of the wall on which it hung, but this would never do for Bradley. With Molyneux he had already solved the problem of adequate illumination at this vital point, and he quickly installed proper lamps with adjustable shutters.

Another thing, the quadrant room was so near the top of the stone wall of the building that the warping of timbers of the roof had caused the lead weight of the telescope counterbalance to rub against the boards. Also, for want of a little oil, the brass cylinder on which the transit instrument turned had become too stiff, and in moving it Bradley broke the screws that held the cylinder to the center part. This required a call from a London telescope-maker, Graham, who took the instrument apart to fix it.

While this was being done Bradley examined the position of the wall quadrant as it hung, and found it out of line by 34½ seconds of arc, an angle that may have seemed practically negligible to Halley, but an error of inexcusable proportions to the careful Bradley.

Finally, when Bradley tried to adjust the telescope of the transit instrument, by checking up against a mark which Halley had placed for this purpose on the park wall some distance away, the Gloucestershire clergyman found that the sight was completely screened from view by the boughs of trees "which had grown up since Dr. Halley had used this instrument."

These boughs were hastily cut away, and then—Bradley found that the mark which poor Halley had carefully set in the park wall actually wasn't on the meridian at all, but 12 to 15 seconds west of it!

VIII

Nineteen years after Halley's death came the year 1761, when the dimensions of the solar system were again enlarged, and the sun pushed back from the earth by a few more millions of miles.

Halley had considered several ways of obtaining the sun's parallax, and discarded them one by one.

"There remains," he then wrote, "Venus's transit over the sun's disc, whose parallax, being four times greater than that of the sun, will cause very sensible differences between the times in which Venus shall seem to pass over the sun's disc in different parts of our earth. From these differences, duly observed, the sun's parallax may be determined, even to a small part of a second of time; and that without any other instruments than telescopes and good common clocks, and without any other qualifications in the observer than fidelity and diligence, with a little skill in astronomy.

"For we need not be scrupulous in finding the latitude of the place, or in accurately determining the hours with respect to the meridian; it is sufficient, if the times be reckoned by clocks, truly corrected according to the revolutions of the heavens, from the total ingress of Venus on the sun's disc, to the beginning of her egress from it, when her opaque globe begins to touch the bright limb of the sun; which times, as I

found by experience, may be observed even to a single second of time."

By this observation, Halley said, it would be possible to find the sun's parallax to within its five-hundredth part, and hence the true dimensions of the solar system with accuracy transcending every measurement possible by other available means!

Little wonder that the entire astronomical world turned out for the great event, which occurred on the morning of June 6, 1761 (Halley had predicted it for the morning of May 26, but in the meantime the calendar reform had acted to add eleven days, so that June 6 New Style corresponded to May 26 Old Style). There were observers ready for the transit at Stockholm and Hornosand, Sweden; Torneo, Lapland, and Tobolsk, Siberia. In the more southerly regions of the earth the transit was observed at the Cape of Good Hope, and in the middle portions at Calcutta and Madras, India; Bologna, Italy, and of course at Paris, London and Greenwich.

But there had come into the picture a complication that Halley had not figured on. The weather was bad, especially in the regions where the best observing instruments were to be had—at London and Paris. At London the sky was overcast most of the time, tho the Astronomer Royal, the Rev. Nathaniel Bliss, who had succeeded Bradley, caught a glimpse of Venus in the sun from the Greenwich Observatory. It was also seen by an observer at Liskeard, Cornwall, and at London by James Short, a telescope-maker of whom we shall hear more in the next chapter. Mr. Short on that occasion used a *reflecting* telescope of 24-inch focus, magnifying 140 times, and while the body of Venus was in the sun he let glimpse into his marvelous new type of instrument no less personages than His Royal Highness the Duke of York, and Their Royal Highnesses Prince William, Prince Henry and Prince Ferdinand!

But for all this worldwide effort; for all the calling out of royalty and the ballyhoo of newspapers, the results were meager and disappointing, not alone because of the unfavorable weather, but more especially (tho Halley had failed to foresee it) because of human liability to error in such observations. Halley had

assumed that all those who took part would be at least as careful and as accurate as himself—or possibly even as Bradley—but there he was mistaken. When the figures came from all parts of the world to be compiled they were marred by the most woeful discrepancies. Tho carefully gathered up by various astronomers, and finally computed by the assiduous Mr. Short, the result did not satisfy most scientists. Short concluded, indeed, that the sun's true parallax (obtained by trying to eliminate the errors in the figures available to him) was 8.52 seconds on the day of the transit, or a mean parallax of 8.65 seconds of arc.

Unlike the earlier estimates, this was proved by subsequent measurements to be too small. It had the appalling effect of removing the sun from the earth by more than 95,000,000 miles. What a far cry from the day of Tycho Brahe, who thought that the sun, by a stretch of the imagination, might conceivably be 4,000,000 miles away!

Following the transit of Venus of 1761, another opportunity to refine the measurement presented itself in 1769, when the planet again crossed the face of the sun. This, too, proved a disappointment. Tho the best instruments were used, and foremost astronomers were sent from England to many parts of the globe to make sure that the observations were accurate, the result still was unsatisfactory. It was found that the exact time of Venus's transit across the bright disc could not be determined within a second of time, as Halley had predicted. It was a matter of judgment at best, and judgments vary even among trained men.

The final parallax determined upon as a result of the two transits was 8.6 seconds; a figure a trifle too small. Today the mean solar parallax is reckoned at about 8.8 seconds of arc.

Chapter VI

THE BATTLE OF THE TELESCOPES, AND WHAT CAME OF IT

I

NOW began a strange and productive rivalry between the two kinds of telescopes: the long-established lens telescopes and the newer mirrors.

We saw in Chapter IV how the Scottish mathematician, James Gregory, first suggested the use of mirrors to overcome the troubles of the older telescopes, and how, tho Newton actually made two small reflectors, the difficulty of figuring the specula precluded the use of these instruments in astronomical work.

Indeed it was fifty years before a real reflector appeared, good enough to tempt the astronomers away from their awkward but useful long telescopes. This instrument was the handiwork of John Hadley, afterward to become world-famous for the invention of Hadley's sextant, an instrument that replaced the astrolabe and cross-staff in navigation and is used to this day on the bridges of the finest ships.

The invention of the sextant came in 1731. Nine or ten years previously, before 1722, Hadley had brought to completion his first reflecting telescope, after a series of labors soon to become a familiar part of the experience of all persons seeking to manufacture instruments of this kind. The success of the venture was a surprise—perhaps as much to Hadley as to science, for since Newton almost no serious attempts had been made to fashion metal into a mirror for the stars. He spent three years testing and improving it, and finally he judged it sufficiently good to call to the attention of the scientific world. He chose to accomplish this by the same method Newton had used in 1672—by presenting it to the Royal Society.

Inspection showed the members of the Society that here was a telescope that could rival the reed-like contrivances of the day, catching more light than the best of the refractors, absolutely without chromatic aberration. Hadley's reflector had a clear aperture of six inches, unusually large then for telescopes of any kind, yet its focal length was less than six feet. The inventor had mounted it with taste and ingenuity, in a wooden tube pivoted in what is known today as altazimuth, with slow motions so that it could follow a star both in altitude and azimuth by means of simple and smooth adjustments. Moreover, it was equipped with a small refracting telescope containing cross-wires, to serve as a finder. The reflector itself was of the Newtonian type, the eyepiece projecting from the side of the wooden tube near its upper end.

As for its usefulness: the astronomers of the Royal Society were not long in testing it in comparison with the 123-foot refracting telescope constructed for the Society by Huygens. The task of making the tests fell to no less a person than James Bradley, assisted by the Rev. James Pound. These worthies first examined the planets with the new telescope, and were surprized to perceive all five satellites of Saturn then known, the division of Saturn's ring, and other difficult objects. Every celestial detail discernible with the 123-foot Huygens telescope was also visible in the Hadley reflector.

Moreover, to view any object with the Huygens instrument was the work of hours (for this ungainly telescope shared the disabilities and unhandiness of its kind), whereas the new Hadley telescope was portable, and could readily be taken from place to place by two men, and operated throughout the test by a single astronomer at the eyepiece.

II

It goes without saying that the report made by Bradley on the performance of this instrument caused a profound sensa-

tion. Hadley became famous. He was besieged by telescope-makers and astronomers eager to learn the secret of his method. In his place, a lesser man might well have considered then whether the procedures he had devised with so much labor and patience were not worth patenting, or at least offering for sale to the highest bidder. But Hadley chose the more generous course; he explained in detail.

Bradley and his friend Molyneux carried news of the new telescope and the method of its manufacture to two London opticians, Messrs. Scarlet and Hearn. These were the first telescope-makers in the world to make reflecting telescopes for the trade. The Scarlet and Hearn reflectors failed to become famous, however. The Londoners never quite got the hang of the process.

It was nearly a decade, in fact, before any professional telescope-makers brought to the making of reflecting telescopes a touch of the kind of genius it needed in those primitive days. James Short, born in Edinburgh in 1710, a telescope-maker later to become one of the foremost of his time, was the first to make really good ones. He became champion of the reflecting telescope in England, and it was to Short that this type of instrument, following its dramatic introduction by Hadley, really owed its great and sudden popularity in the middle years of the eighteenth century.

Short's interest in telescopes began while he was still a very young man. His first mirrors, curiously enough, were made of glass, but tho Short was able to give these specula the proper figure, he could find no satisfactory means of providing a good reflecting surface, since the art of chemically depositing silver on glass had not yet been invented. He turned finally to the more difficult, but for his time more satisfactory, medium of speculum metal, the same as that used by Hadley in his successful instrument.

The subject of speculum metal deserves a little special consideration at this point, for this substance was to play an increasingly important rôle in the subsequent development of the great mirrors. Newton disclosed in an early paper that he had

used bell-metal for his two small reflecting telescopes. This is an alloy of copper and tin, and in the seventeenth century was often whitened with arsenic, an old trick of the alchemists who thought that this whitening gave the metal some of the characteristics of silver.

Short also used an alloy of copper and tin, as did Hadley, but the proportions employed by these telescope-makers were not the same as in ordinary bell-metal. The Hadley and Short alloys, in fact, were very close to the specific mixture known today as *speculum metal,* an alloy consisting of exactly four atoms of copper for every atom of tin. This is a particularly difficult material to cast and work, because it is even more brittle than glass and often cracks during cooling in the mold. Once cooled, it is so hard it can scarcely be scratched with a file, and if dropped it will shatter like fragile china.

Compensating for these unattractive qualities, this metal lent itself excellently to the uses of the telescope-maker. The curvatures could be obtained by grinding the speculum first with emery on a properly-shaped tool, and later with a different tool made of optician's pitch surfaced with jeweler's rouge. In the end it took a beautiful polish, needed no other surfacing for the reflection of light, and resisted tarnishing for a considerable period. A freshly polished mirror of speculum metal, tho it actually does not reflect quite as much light as a silver-on-glass mirror, appears brighter than polished silver, and is a beautiful thing to see.

But mirrors made of speculum metal are not permanent. Sooner or later every speculum-metal mirror will tarnish, and this discoloration very rapidly cuts down the reflecting power. When tarnishing has reached such a point as to interfere seriously with the use of the instrument, the speculum requires repolishing—a job that can be done only by an expert. It means *refiguring* (reshaping the curvature) in many cases, for the business of scrubbing off the tarnish changes the contour of the mirror sufficiently to ruin it. Often the characteristics of the speculum will be entirely altered, even to a wide change in

focal length. Only a workman as skilful as the original maker of the mirror can guarantee a satisfactory outcome.

When it is remembered that this repolishing nuisance was a matter of great frequency, some alloys requiring repolishing every two or three months, it is easy to understand the troubles that beset astronomers of those times; they had no choice but to use a long and awkward telescope of the refracting variety, or accept one of Short's speculum-metal reflectors together with the bother and expense of keeping it in condition. It speaks well for the remarkably good mirrors he made, and for the excellence of the alloy employed, that Short was a great favorite. A few of his instruments are said to have had so fine a polish that they retained it for several years.

The fame of his instruments we may judge by the fact that it was with this optician and his reflecting telescopes that His Royal Highness the Duke of York and the Princess chose to view the transit of Venus in 1761, rather than with the Astronomer Royal and the already outmoded instruments at the Greenwich Observatory.

III

In the beginning of the rivalry the reflecting telescope had undoubtedly taken the lead, but it was not to hold it undisputed for long.

The refracting telescope, in the doldrums more or less since Newton had come to his famous decision that it could not be further improved, had ardent and able supporters. Their courage to dispute the dictum of the great master of eighteenth-century science came from a firm tho erroneous belief that the human eye, with its various humors, is an example of an *achromatic* optical instrument. If nature, by combining various refracting materials, can produce such an instrument, why cannot man?

One of the early adherents of this theory was the Scottish mathematician Gregory, who invented the reflecting telescope. A more effective believer was Chester Moor Hall, a gentleman of Essex, England. After several years spent in thought and

experiment, Hall devised a telescope objective composed of two pieces of glass, one crown and the other flint, in such proportions and shapes as to produce an instrument which was for all practical purposes without color aberration. In 1733 he revealed his discovery to George Bast, a London optician, and ordered him to make one of the instruments. Bast subsequently made not one but several.

Strangely, Chester Moor Hall's achromatic telescopes caused little stir. Possibly he was in error in not presenting the first of them to the Royal Society, a method which in that day seemed a certain way of bringing a new invention to public attention. Perhaps, also, the telescopes themselves were rather more interesting than useful. The glass available to Hall and his associates was of poor quality, precluding the making of any but small telescopes, and those of uncertain value.

How many of them were actually made will probably never be known. Bast gave the secret away to several other opticians, who also tried their hand at achromatics, with indifferent success. Then the whole matter died down, and it was twenty-five years before another inventor tried to resuscitate the refracting telescope.

The new savior was John Dollond, a former silk weaver turned optician. In 1758 he announced to the Royal Society that he had solved the problem of achromatic lenses. The scientific worthies of that body immediately hailed it as a new invention. They awarded the Copley Medal to Dollond for the achievement, and made a great to-do. Apparently in all the time that had elapsed since 1733 no important member of the scientific world had heard of Chester Moor Hall; an almost incredible situation in a period when science was seeking new fields perhaps more restlessly and with greater penetration than ever before.

Possibly Hall's discovery was not considered important because he had failed to bolster it up with a proper series of laboratory experiments. Shrewd John Dollond was careful to capitalize on the impressiveness of a learned report. He told the Society that he had arrived at the proper combination of lenses

through a long, dark period of wrestling with the unknown, during which he had tried almost innumerable possible refracting substances, ranging from lenses of the hardest quartz and glass to lenses of water and solutions.

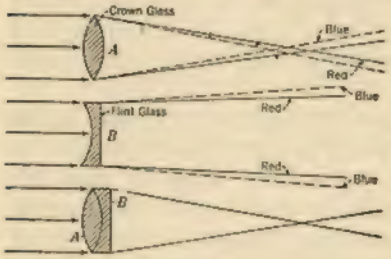


FIG. 21

The Principle of the Achromatic Lens. The convex lens of crown glass A brings the red and blue rays to different foci. The concave flint-glass lens B has the opposite effect. Combined, they bring both ends of the spectrum to focus at the same point.

Little good did it do Hall to point out then that he had actually made the identical discovery without the aid of such experiments. Who would believe him? Hall and his friends even went to court in the matter, to prevent the issuing of a patent to the Dollonds, father and son, who had immediately applied for one. They produced good evidence that Hall had actually been the first inventor of the instrument; also that Dollond had had ample opportunity to learn about the Hall telescopes and could have discovered their secret with much less difficulty than that described to the Royal Society.

But the weight of public, scientific and legal opinion was in favor of the optician. To John Dollond and Peter Dollond, his son, went the patent and the credit. And there, perhaps, they belonged, for these opticians were quick to turn the invention to practical account, whereas in the hands of Hall it had languished for more than two decades. The Dollonds promptly began the manufacture of achromatic telescopes, and what with the publicity the new instruments had received, and their general excellence, they soon made great headway.

In principle the John Dollond object glasses were the same as those used today. They consisted of a convex lens of crown glass combined with a concave lens of flint glass. The concave lens was less powerful than the convex; the result of the combination therefore was to converge the light as a single

convex lens would do. But the flint glass, having a much wider difference in its ability to refract the light of different colors, was sufficiently strong to correct the color dispersion inevitably introduced by the more powerful lens of crown glass (Fig. 21).

In 1765 Peter Dollond introduced a second type of achromatic objective, consisting of three pieces of glass—a "sandwich" in which a concave lens of flint glass was held between two convex lenses of crown glass. This type, too, is still employed in modern telescopes, as well as objectives containing four or more pieces.

IV

By such simple means was the era of the long telescope brought to a close. With what a sigh of relief the old astronomers must have seen it go! The refracting telescope, thanks to the Dollonds, was once more on a competing basis with the reflector. It was, in fact, in a better position than its rival, for the refractor, tho expensive, was a permanent instrument, requiring no frequent repolishing.

Such a distinctive advantage would probably have won supremacy for the new refractor in much less time than it actually took, had it not been for the appearance, almost before the Dollonds had got into factory production, of one of the greatest geniuses of the eighteenth century, the founder of modern stellar astronomy. This man, as chance would have it, was a champion of the reflecting telescope.

He was William Herschel, a musician who moved from Hanover to London in 1757 and subsequently set the world afire with such a flame of interest in astronomy as it has enjoyed neither before nor since.

Herschel's conversion to astronomy appears to have been entirely accidental. During his first ten years on English soil he applied himself assiduously to his musical art, with the result that by 1767 he was comfortably established in Bath, an oboist in a noted orchestra and organist in the famous Octagon Chapel. Ultimately he became director of the orchestra.

But he was vaguely discontented with this life, and was

casting about for some hobby that would lead him into a larger world. In 1772—a fateful year for astronomy—he borrowed a small Gregorian reflector from a friend, to do a little casual exploring of the skies. Here, he saw instantly, was the world outside himself that he had been looking for; here was the universe, waiting to be surveyed!

Characteristically, he immediately began to lay large plans. His scheme was nothing smaller than a study of the entire heavens, to be done by one man, with the finest obtainable telescope, the object being to see whether such a survey would not produce order out of astronomical chaos, and reveal *meaning* in the universe which had so far escaped the astronomers and the philosophers!

But where could a telescope adequate to this task be obtained? Herschel had too little money to buy one of the expensive Dollond achromatics. Even the mirrors by Short were beyond his means. Nothing daunted, he tackled the problem of making his own telescope, as Huygens had done before him, and Hevelius and Galileo. At first he tried a small refractor, but the glass available in his time was too poor, he soon perceived, for the manufacture of telescopes of sufficient aperture for his plans. Reflecting telescopes appealed to him as more likely to produce suitable results, and he determined at once to learn the arduous and exacting business of making them.

It is recorded that he made and polished more than 200 small mirrors before one was obtained that could be called successful. The amount of work represented by so many failures is colossal. In Herschel's day a telescope-maker was unable to purchase blanks all ready for the grinding and figuring; his first task was to melt, mix and cast the difficult and contrary speculum metal. Then, if the cast turned out successfully (as frequently it did not), he was ready to undertake the next and successively more exacting jobs of grinding, polishing and figuring it.

Each of these three steps in the making of a mirror is distinct and separate, and must be accomplished by different means. The grinding consists in producing a spherical concave surface

on the disc. This is then polished to make it a mirror, after which flaws in the spherical curvature can be tested for and removed. The final and most delicate process of all is that of figuring, in which the spherical curvature is slightly deepened at the center to produce a paraboloid.

Since Herschel's time simple tests have been devised by means of which the curvature can be tested accurately as the work progresses. But then the art of making specula was young; the telescope-maker had to judge a great deal by the "feel" of the thing, had to depend on his methods of grinding and lapping to produce a regular figure. To Herschel this meant long, tedious, backbreaking hours of steady work—hours during which he walked around and around a pedestal upon which his grinding tool had been set. On at least one occasion, mentioned by his sister Caroline, he worked continuously for sixteen hours on a single grinding operation, never once taking his hands off the work or stopping the monotonous motions upon which he depended for the exquisite exactness of his figure.

Out of these Herculean labors eventually came telescopes—with fine, highly polished mirrors—such as the world had never seen before. By 1774, two years after his initial voyage among the stars with a borrowed Gregorian, Herschel had the satisfaction of viewing them again with an immeasurably better one, a Newtonian telescope of 6-foot focal length made entirely by his own hands.

Soon afterward he completed a 7-foot Newtonian of 6¼-inch aperture. This telescope was tested at Greenwich Observatory against one of Short's finest mirrors of 9½-inch diameter, and so remarkable was the figure of the Herschel instrument, so excellent its polish, that the larger instrument, made by a man who had been famous for years as a manufacturer of reflecting telescopes, came out a poor second.

But this, after all, was only preliminary to Herschel's plans, and greater triumphs were in store for that particular 7-foot reflector and its maker. In the year 1781, near the beginning of his methodical review of the heavens, Herschel came upon a moving object which he at first thought was a new comet; but

upon further observation it proved to be a planet lying in an orbit beyond Saturn—the first planet to be added to the solar system by the telescope.

The effect of this discovery was tremendous, both upon William Herschel and the general public. Almost overnight the astronomer became famous. He was awarded the Copley Medal by the Royal Society, elected a fellow of that great body, and received a flattering offer of aid from the King, who was the same fat and vapid George III who a few years earlier had so goaded the people of America by his stupidities and taxation that they had put up a successful revolt.

The King had lost a continent, but in Herschel's discovery he thought he had gained a world. The astronomer, partly no doubt because he needed the King's patronage, partly also from patriotic zeal, played up to this fulsome notion. In a communication filled with the most revolting flattery, Herschel told the King that the name of the new planet should not be akin to those of the other planets, honoring as they do the mythical gods and goddesses; it should bear a modern name perpetuating forever the memory of a great man, King George III. With a flourish, he therefore christened it "Georgium Sidus," or George's Star—a name, needless to say, that found little favor outside the royal household, and which was speedily replaced with the appellation by which we now know Herschel's planet —*Uranus*.

Herschel had attracted the King's attention, nevertheless, and in 1782, the year following the discovery, he accepted an invitation to become the King's personal astronomer. George III's favor, it is to be noted, did not bring any great reward. He was niggardly, even in paying for a new planet, and Herschel's financial straits were not relieved until, in 1788, he married the wealthy widow of a London merchant.

V

Of course it is not fair to judge Herschel and the quality of his work by the unpleasant episode of the naming of the new

planet. His was an unusual combination of genius—a great instrument-maker and a great astronomer in one. From the year 1774, when his first telescope was finished, he divided his waking hours into two parts. During the night, on every one that was clear, he gazed systematically at the heavens. In the daytime and during those nights when clouds obscured the view, he made specula and telescopes.

He was more than an astronomer and a telescope-maker; he was a high priest of these arts. It was with a burning zeal that he approached them; they were his life's devotion, and neither fame nor success nor the approbation of a King could sway him from the continual application of his talents.

Fortunate it was for Herschel, the astronomer, that Herschel the telescope-maker was so skilful; else where would he have obtained the constant stream of bright specula needed for his nightly search of the heavens? The need for continual repolishing, which Herschel had inherited from his predecessors, was not overcome during his lifetime. In fact, he found it necessary to repolish rather more often than others among the professional mirror-makers of the time, for it appears that he never succeeded in mastering the difficulty of casting the hardest variety of speculum metal, but used instead a somewhat softer alloy, one that worked up beautifully and took a marvelous polish, but which, as tho exacting payment for these excellent qualities, tarnished rapidly and soon needed reworking.

For his smaller telescopes Herschel kept relays of specula ready, and changed them as soon as there was a noticeable falling off in reflecting power. For his larger instruments, he devised polishing and figuring machines which rapidly shaved down the old, tarnished surface, and put on a new figure and polish in a few hours.

Herschel realized, as had many astronomers before him, that farther voyaging into space would require the capture and transmission of more light. There were two ways of achieving these ends: by enlarging the aperture—a method that soon increases the cost and labor of the telescope to a tremendous degree—and by improving the arrangement of the instrument.

in order to make use of more of the light that falls upon it. Now, speculum metal does not reflect as much light as a coating of silver; moreover, it does not make as effective use of the light as a refracting telescope. A great deal of the radiation is not reflected from its surface at all, but is absorbed. When, as in the case of the Newtonian and other standard types, the light is *twice* reflected, loss from this absorption may amount to 40 per cent or more — a shocking waste to a man like Herschel, who was out to see as far into the universe as the ingenuity of his invention and the perfection of his instruments would permit.

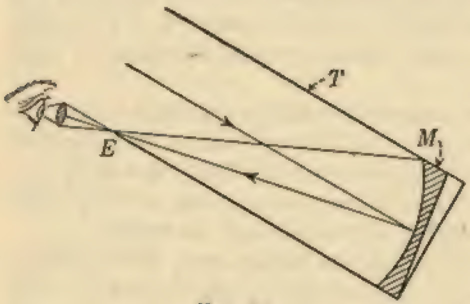


FIG. 22

Scheme of the Herschelian Reflecting Telescope. The concave mirror M is tilted in the tube sufficiently to bring the image to focus at the outer edge E, where the eyepiece is affixed.

Accordingly, he devised a fourth type of reflecting telescope, called the *Herschelian,* which has no need for a second mirror. In this the large mirror is slightly tilted—just enough to bring the image to the side of the telescope tube at its outer end. Here an eyepiece is affixed, and the astronomer stands at the end of the tube, looking down toward the mirror (Fig. 22).

Having cut down his light loss by half through the adoption of this system (which nevertheless had many objectionable features and is seldom seen today), Herschel also pushed out in the other direction, toward larger and larger instruments.

He made a successful 12-inch mirror in 1782. In 1788 he completed a speculum 18 inches in diameter with a focal length of 20 feet; an extraordinary accomplishment. Then, pleased with the success of these, he grimly undertook a fantastic leap into the future. Why waste time increasing the diameter of the telescope by slow degrees? Why not make a really large one, and have the matter over with?

Accordingly, he laid plans for the construction of a telescope 48 inches in diameter, with a focal length of 40 feet. The making of such an instrument would be a matter of some note even in these times, when suitable material and the finest of grinding machines are available. It was all the more remarkable in Herschel's day because he was forced to use the same kind of speculum metal as in his earlier instruments, and the same kind of grinding machines he had devised for their construction.

The finished speculum, completed in the summer of 1789, was 49½ inches in diameter, 3½ inches thick, and when cast weighed more than a ton. This mirror he placed in the lower end of a wooden tube 48 inches in diameter and 40 feet long, Herschelian style, and swung the tube into a frame mounted on a circular track, so that the whole apparatus could be moved around the horizon as a unit. The tube of the telescope was elevated or lowered by means of blocks and tackle. The observer perched at the mouth of it, peering down into that black well through a Huygens eyepiece (Plate 10).

It was a marvelous instrument, a monument to the greatest astronomer of the era, and he was rewarded by observing, almost on the day of its completion, two new satellites of Saturn, those known as Enceladus and Mimas.

It is interesting to note that Herschel in all his life failed to appreciate the convenience of the equatorial mounting, and for some reason preferred to mount his instruments on a sort of glorified altazimuth.

VI

The great flood of new discovery that attended Herschel's rise in the astronomical world did not wait upon the completion of his Cyclopean 48-inch instrument. From the time he first looked into the sky with his own telescopes he sent a constant stream of reports to the Royal Society. His discovery of Uranus doubled the known diameter of the solar system. He was first to

observe the whitened spots at the poles of Mars, which he concluded to be snow or ice like that upon the poles of the earth. He studied Saturn and his satellites, and the satellites of Jupiter, and found them conforming to laws that govern the motions of our own moon.

Indeed, the field of planetary exploration soon became too small for him, and Herschel launched out into the vasty deeps of the starry firmament—the first of all the astronomers really to do so. Lacking his instruments, others had been interested mainly in seeking the parallax of some of the fixed stars, and in determining their distance from the earth. Herschel's interest transcended parallax; he sought not so much to measure as to understand.

This new interest in what lay beyond the narrow confines of the solar system was to a degree stimulated in Herschel and his contemporaries by some interesting theories of the structure of the universe then current. Notable among them was that advanced in 1750 by Thomas Wright, who believed that the universe is shaped like a grindstone; hence the apparent clustering of the stars in the Milky Way, which is nothing but the rim of this grindstone.

Pondering on this theory, Herschel let his hungry telescope move speculatively among the stars, and was soon able to produce some additional proof for it. Moreover, he perceived that many stars are not single bright points of light, as they appear to the eye or in small telescopes, but are double, the two stars of the pair revolving around each other as the earth and moon revolve around their common center of gravity.

Now he went questing even farther into space, and became one of the earliest observers of the great nebulæ, or island universes. In his lifetime he increased the number of known nebulæ from 103 (observed by Charles Messier in Paris) to more than 4,000. And in 1785, crowning his earlier discoveries and speculations, he projected the general course of the sun's motion through space, basing his calculations on the observed "proper motions" of thirteen stars, the apparent displacements of which, he argued, were not due to the travels of the stars

themselves, but in part at least to the steady, swift progress of our own system.

It is hard to understand how such a man could have found time, what with his own observations and the need for continually repairing the telescopes with which he made them, to construct like instruments for others; nevertheless he did. As his fame spread, the demand for Herschel telescopes was almost insatiable. The prices they commanded rose in proportion. An early telescope of 7-foot focus was sold for 200 guineas (about \$1,000), but later he received £3,150 (about \$15,000) for one bought in Spain, and £2,300 (\$10,000) for two made on order for Louis Bonaparte.

VII

For all the popularity William Herschel brought to it, the reflecting telescope languished with his passing. Even during his lifetime astronomers generally were casting about for better glasses to replace their tarnishing, cantankerous reflectors. To operate a reflector in those days required not only that the astronomer be a fine observer, but also a combination of metallurgist, mechanic, blacksmith and instrument-maker as well, ready and able at all times to take the mirror out and give it a thorough polishing and refiguring.

Now, the ideal combination, so well exemplified in William Herschel, is not found twice in a generation. In fact, the only other important astronomers to use large specula in the period just following Herschel's death in 1822 were his son, John Herschel, and Lord William Parsons, third Earl of Rosse, who established an observatory at his seat, Parsontown, Ireland, about 1825.

Lord Rosse, like Herschel, was a born telescope-maker. His greatest fame rests on his construction of a 6-foot mirror, the largest ever attempted up to that time, and indeed the largest ever made with speculum metal (Plate 11). He began the work in 1842, and in 1845 had finished and mounted it. From 1848 to 1878 it was used almost constantly for observation. Lord

Rosse, with the aid of this instrument, was able to reveal many new features of nebulæ, especially the character of annular and planetary nebulæ, and the spiral figure of such "island universes" as the Great Nebula in Andromeda.

But even while this great reflector was doing its best work, it had become an anachronism and a curiosity. The refracting telescope, so long in eclipse, was again having its day. The beginning of the new rise came with the appearance of better optical glass, an achievement due almost entirely to the genius of Pierre Louis Guinand, a Swiss artizan who made bells for a living, and who became interested in glass when he imported some from England for the construction of a telescope—and found it poor.

It occurred to Guinand that a way ought to be discovered for making better glass. Beginning about 1784 he inaugurated a long series of experiments in this difficult art. What money he could earn at his trade of bell-making went into his furnaces. Failure after failure was his reward. But Guinand was a sticker; each failure caused him to redouble his efforts, until at last, shortly before the dawn of the nineteenth century, he began producing flint glass of flawless character in discs suitable for optical use, and often as large as 6 inches in diameter.

The fame of this Swiss bell-maker who had tamed the glass furnace went beyond the borders of his country. In time it reached Munich, where a young man, Joseph von Fraunhofer, later to be known as the "father of astrophysics" for his invention of the spectroscope, was hard at work studying the behavior of light. Guinand was persuaded in 1805 to join Fraunhofer at Munich, where he taught the young German, then only eighteen, the secrets of the mystical art of making optical glass. Later he returned to Switzerland, and there continued the work of making larger and larger optical discs. He died in 1824, and his son Henry, moving to Paris, carried with him the treasure of optical knowledge amassed by his father. From that point the new art went out in several directions—to England, to Germany, and finally to America.

Meanwhile, the refracting telescope had again come into its

own, after a long and distinguished history of success and disappointment. Fraunhofer, using the good glass he had learned to make under the patient and expert tutelage of Guinand, devised a form of objective slightly different in curvature from John Dollond's, and of a perfection unsurpassed in any lenses of this day. It consisted, as did Dollond's objective, of two pieces of glass—a convex lens of crown and a concave lens of flint glass. But the convex lens does not have the same curvature on both sides, the radius of the front curvature being about 2½ times longer than the back. Moreover, the curves of the convex back of the crown glass and the concave surface of the flint glass do not quite match, the flint being just a trifle flatter than the crown.

With this combination Fraunhofer was able to make instruments of remarkable size and usefulness. His first large telescope, one of 9.6 inches aperture and 170 inches focal length, was used by Friedrich Georg Wilhelm Struve, the great Russian astronomer, at the University of Dorpat for the observation of double stars. Another of his instruments was the divided-lens telescope with which Friedrich Wilhelm Bessel was able to determine, for the first time in history, the parallax of a star, inaugurating a long series of spectacular discoveries which put the refracting telescope again in the ascendant, proving that this instrument, as fashioned by Fraunhofer and his contemporaries, could reveal the heavens quite as well as the great speculum-metal mirrors of Herschel and Rosse, and with less fuss and inconvenience.

For example, it was with a refracting telescope that the Italian astronomer Giuseppe Piazzi, first director of the Observatory at Palermo, added a new if tiny planet to the solar system on the first evening of the year 1800. This wanderer he discovered flying through space in an orbit lying between Mars and the giant Jupiter, in a region which theory had earlier shown should be occupied by a planet, tho none had been found.

Piazzi's planet, which he named Ceres, turned out later to be one of a swarm of small, broken worlds; mere chunks of rocky matter swinging in greatly perturbed orbits around the sun;

fragments, some think, of a large planet which was broken up by a too-close approach to Jupiter. About 1300 of these minute worlds have since been discovered, some of which approach closer to the earth on occasion than any other body except the moon.

Bessel, by proving in 1838 that he had at last detected the true parallax of a star, succeeded in showing that the universe is at least as large as Bradley had earlier concluded it was. For the parallax of the star *61 Cygni,* he found, is a little more than three-tenths of a second of arc, which would indicate that this star is distant from the sun 657,700 times as far as the earth is, or an enormous total of nearly 61,825,000,000,000 miles!

Then Struve, first at the University of Dorpat and later at the fine new Russian National Observatory at Pulkowo, confirmed the conclusion of the Herschels as to the number of double stars. He found that perhaps as many as a third of the stars in the firmament have companions revolving with them around a common center. Some of these companions were visible to Struve through his fine Fraunhofer telescopes, others were shown to exist by the evidence of the orbital motions of the bright member of the pair, but the stellar companions were—dark stars!

Bessel also studied double stars, and succeeded in making the discovery that even the great star Sirius is to be classed among them. Sirius obviously was a double, but Bessel was unable to sight the companion. That honor was reserved for an American, Alvan G. Clark, son of the first American telescope-maker, who saw it in 1862 with an 18½-inch refractor figured by his father.

For indeed, by the middle of the century the art of telescope-making had actually crossed the Atlantic, and the portrait painter Alvan Clark, who turned to telescope-making when he was in his middle age, had founded a firm which today is still one of the leading producers of fine telescopes for the observatories of the world. Clark's telescopes were refractors, a measure

of the triumph of the lens telescope in that day over its rival, the speculum-metal mirror.

VIII

But the reflector was soon to be rescued—more, to be given such an impetus this time that the refractor, tho always to be an important instrument and indispensable for some kinds of work, may never again catch up in size, magnificence, or popular appeal to astronomers and the public.

The foundation for this new revolution in telescopes was laid by studies of the salts of silver which had begun even in John Herschel's time, and which led ultimately both to the improvement of the reflecting telescope and the invention of photography, a pair of discoveries which were to have a more profound influence on the future of astronomy than perhaps any other except the invention of the spectroscope, or of the telescope itself. These experiments with the salts of silver resulted, apparently accidentally, in a method by which this bright metal could be coated evenly and thinly over a surface of glass in such a way as to produce a shining reflecting surface without appreciably changing the contours of the figure.

The first man to take the obvious step and build a telescope with such a mirror, was the German physicist, Dr. Karl August Steinheil. On March 24, 1856, he published in the *Allgemeine Zeitung* at Augsburg, Germany, an account of his success with a small glass speculum coated with silver. The instrument had an aperture of 4 inches and a magnifying power of 100. Dr. Steinheil stated that it gave a remarkably good image.

In the following year, application of the silvering process to telescope mirrors was rediscovered, quite independently, and announced to the scientific world by a man whose name was already one to conjure with. Only two years previously he had received the Copley Medal of the Royal Society for his famous demonstration of the rotation of the earth (by means of the pendulum), for his invention of the gyroscope, and for his use of a rapidly revolving mirror for measuring the velocity of light.

He was the distinguished French physicist, Jean Bernard Leon Foucault, and to him the reflecting telescope is indebted not only for his aid in perfecting the process of silvering glass specula, but also for his excellent practical method of figuring and testing for the proper paraboloid of revolution, the figure used in all but certain experimental and special reflecting telescopes to this day.

Foucault fortunately made no effort to keep his improvements on the reflecting telescope secret, or to conceal his methods of obtaining them. The result was that anyone having the requisite skill and patience could thereafter make silvered reflectors, and many did. In our day, the small reflector has become known as the "poor man's telescope," because one can be made by anybody of sufficient skill, for an outlay of a few dollars. It is the telescope widely used by amateur astronomers, many of whom make their telescopes with their own hands. Probably more than 10,000 such small reflecting telescopes, homemade, have been constructed in America alone in the last few years.

The reflecting telescope today is also the instrument of the great observatories. These giants are not "poor men's telescopes" by any means, for they cost hundreds of thousands, and in some cases millions of dollars, and are our chief means of exploring the outermost depths of space.

The refracting telescope has not been superseded, however—far from it. The great battle of the telescopes has finally turned out a draw. Today the telescopes are no longer rivals but companions in the quest for astronomical knowledge. In part this is due to the fact that their special excellences give each kind of telescope a special job to do, and in part to the fact that, so far as performance goes, there is no longer any real choice between them.

In general, the refractor is the better instrument when fine detail is required, as in the study of the planets. The refractor, however, is not as useful as the reflecting telescope for the exploration of space, the observation of distant stars, nebulae and other objects at great distances from the earth.

For though the refractor often has better resolution, there are definite limitations to its practical size, and hence to its light-gathering power. The big 40-inch refractor at the Yerkes Observatory appears to be the maximum development in this direction. Lenses larger than three feet and a half in diameter, even if they could be cast and figured successfully, would probably produce internal strains by their own weight sufficient to ruin their optical qualities.

No such obstacle appears to limit the size of reflectors. These giants have grown larger and larger. The Hooker reflector now in use at Mt. Wilson Observatory has a diameter of 100 inches, and the Mt. Palomar telescope has a mirror 200 inches across.

Chapter VII

THE CAMERA AND THE SPECTROSCOPE BECOME HANDMAIDENS OF THE TELESCOPE

I

IN the first quarter of the nineteenth century were laid the foundations for two inventions destined to rank next in importance to the telescope. These had quite different beginnings; neither was specifically developed for astronomical use, and yet when they had become established they revolutionized astronomy quite as much as the first telescopes did in the hands of such geniuses as Galileo, Huygens, Cassini, Hevelius and Halley.

The camera, curiously, is considerably older than the art of photography. In the form of the *camera obscura*, a device for throwing an image sharply on a plate or screen for the assistance of artists and lithographers, it had been known for years. It did not form a permanent, reproducible image, however, until a painter who had been experimenting with silver salts—Louis Jacques Mandé Daguerre, discovered about 1824 that some of these salts were sensitive to light.

Meanwhile a somewhat similar discovery had been made by another Frenchman, the lithographer Joseph Nicéphore Niepce, who had been seeking a way to transfer the image of the camera obscura directly to stone or metal without the intervention of a skilled and high-salaried artist. About 1829 these two men—one with an idea and the rudiments of a process, the other with a need and considerable practical experience—formed a partnership. Ten years later, on August 10, 1839, they made the startling announcement before the French Academy of Science, at Paris, *that they had learned how to obtain a permanent copy*

of the image which the camera obscura can be made to throw upon a plate.

In these days when photographs are common experience, when they look out at us from newspapers and books, when every person at some time or another has had his own portrait made by photography, when most persons own or at least have operated a snapshot camera, the import of that announcement is likely to be missed. Until the day when Daguerre and his partner Niepce first brought their metal plate out of its chemical bath and perceived that they had actually caught an image, there had been no pictorial representations of any kind in the world which had not been made through the intervention of an artist; and hence which reflected his own personality and viewpoint quite as much as (and usually more than) the actual appearance of the article pictured.

But now these two obscure Frenchmen had a picture not made by an artist, but by the sun itself; a picture which represented in exact proportions the object as it looked to the eye!

Small wonder that there was a sensation at the announcement. Daguerre, the real inventor, named the process after himself, and photographs made by his method immediately became known as daguerreotypes. As a reward, the French Government gave him a pension of $1,200 a year for life, honored him as a benefactor to the nation, and on the theory that the new invention was too great a boon to humanity to keep as a monopoly, made his process public.

It was not an especially complicated method, but the success of it, as many an amateur as well as professional photographer was soon to discover, depended on the skill of the operator, on the care with which each operation was performed, and above all, on knowledge of the precise length of time needed for the exposure.

In the daguerreotype process a silver-coated copper plate was buffed and burnished to a high polish, and then was carefully exposed to the fumes of iodine. This produced upon the surface a fine layer of silver iodide, a fairly sensitive salt, but one which had to be exposed in the camera for about 20 minutes in

bright sunlight. The image so formed was then developed by placing it over a cup of hot mercury, and finally fixed in a bath of thiosulfate of soda.

The resulting photograph, elderly persons will remember, was a foggy, brownish affair, of which only one copy could be made. Yet those old daguerreotypes took the picture-hungry world by storm. The daguerreotype process remained the dominant method of photography for more than a decade, until it was superseded by the collodion or wet-plate process about 1851.

As its chief advantage, the second method had a great reduction in the time necessary for exposure. It was the invention of an English architect, Scott Archer, and a process of this type is still used in architectural offices for the reproduction of drawings. Archer prepared his photographic plates by mixing a solution of collodion, a cellulose product, with ether and alcohol, to which was added a soluble salt of iodine and a little bromine. This was coated on one side of a clean glass plate, and kept in this condition until the photographer was ready to use it.

The sensitization was accomplished just before insertion in the camera, and had to be done in a dark room. The collodion-coated plate was dipped into a bath of silver nitrate, then slipped into the camera and the picture taken. The exposure of necessity was made while the plate was wet, and was developed immediately by pouring over it a solution of pyrogallol containing a little acetic acid. The fixing required the use of the same chemical utilized by Daguerre, thiosulfate of soda, but a little later cyanide of potassium was substituted.

In addition to the greater clearness of the picture and the shortness of exposure (a few seconds), the wet-plate process had an additional advantage in that the glass plate permitted contact printing on sensitized paper; hence any number of copies of the original negative could be made. In a short time the wet-plate process completely superseded the daguerreotype and remained in vogue until it in turn was replaced by the gelatine, or dry-plate process, developed as the result of experiments carried on by Dr. R. L. Maddox in England after 1871.

The introduction of Dr. Maddox's gelatine process for the

first time made photography possible as a widespread popular pastime, and the enormous crop of amateurs that appeared accelerated the development of sensitivity, convenience, sharpness and other qualities found in the photography of today.

II

The application of photography to astronomy did not wait upon these later developments. Imaginative men, among them the French astronomer Dominique François Arago, were quick to see the possibility of supplementing the work of their old friend, the telescope, with the product of this new invention. Arago, in 1839, the very year in which Louis Daguerre's marvelous contrivance first came to public notice, called the attention of the Academy of France to the possibilities of photography in extending the powers of the eye in astronomy.

It was not a Frenchman, however, who first applied the new art of photography successfully to a telescope, but an American. The word of Daguerre's invention had spread over the world with great rapidity. Within a few days practically every scientific man in Europe had heard of it. It happened that the American artist, Dr. Samuel F. B. Morse, later to become famous as the inventor of the telegraph, was in Europe at the time, and returning to America shortly afterward, he brought word of the invention of photography to his colleague, Dr. John W. Draper, of New York University. What is more, he brought formulæ for the process in such detail that Draper was enabled immediately to try his hand at the new art.

The New Yorker tested out his skill and technique by making human portraits with the daguerreotype. He was the first person ever to do so, for Daguerre and his colleague up to that time had experimented chiefly with inanimate objects in their work and demonstrations, the reason obviously being the long exposure necessary for a good reproduction.

The success of his human portraiture sent Draper scurrying about for other subjects. In 1840, the year following Daguerre's announcement, he succeeded in fitting a plateholder to his

telescope, and on a night when the moon was full made a long exposure of it. The result was not much of a photograph, as such things go today. The image of the full moon was less than an inch in diameter. Practically no details of the lunar landscape were visible. Nevertheless, it was a much finer portrait than Daguerre himself had made when, two years previously, he had also tried to photograph the moon. On that occasion the developed plate showed only a faintly lightstruck blur.

Up at Harvard Observatory, Professor William Cranch Bond, the director, and his son George P. Bond, were soon interested, as Dr. Draper had been, in the astronomical possibilities of the photographic plate. It was apparent to them, after some preliminary experiments, that the daguerreotype would need improvement in sensitivity before useful astronomical photographs could be taken. Fortunately this improvement came, about 1850, when the length of time needed for exposure was greatly cut down. Using this improved daguerreotype, George P. Bond, aided by Messrs. Whipple and Black, photographers of Boston, at length obtained some photographs of the moon which were a considerable improvement over that made by Dr. Draper.

The first of these was taken December 18, 1849, with the great 15-inch refractor of the Harvard Observatory. A year later an even better one was obtained. It proved so good that it was sent to London for the Great Exposition of 1851, and there became one of the outstanding exhibits of the show. It was, in fact, the first photograph of the moon to show a distinct image, and it contained in addition a little lunar detail.

Over in England another experimenter was busy. He was Warren de la Rue, an ingenious young man whose insight into the problems of lunar and solar photography soon brought him many honors. He perceived that the daguerreotype was strictly limited in its results, and cast about for a new and better process. In 1857 he presented to the Royal Society positive copies from a negative collodion photograph. De la Rue had been at work on this method for five years before he had learned to adapt the messy wet plates to use with a telescope.

Meantime, the stars had not been neglected, tho obviously this was a somewhat more difficult problem than photography of the moon. The first picture of a star was taken on July 17, 1850, at the Harvard Observatory—a daguerreotype. The star which sat for its portrait on that occasion, the photographer being Mr. Whipple of Boston, working under the direction of George P. Bond with the 15-inch refractor, was *Alpha Lyræ.* A few days later the same pair of experimenters also were able to take a photograph of the bright star *Castor.*

It must be confessed that the results of these daguerreotype efforts in stellar photography were not very successful. For one thing, the plates were too insensitive, and long exposures were required to obtain anything at all. For another, the driving clock of the great 15-inch equatorial telescope, while accurate enough for visual observation, was too irregular for photography, so that the images that were obtained looked more like roughened light-struck blobs than star images.

Subsequently, George Bond and his photographic colleagues passed several years in experiment, limiting their efforts mostly to photos of the moon and sun and to the improvement of their apparatus. In March, 1857, they again turned their attention to the stars, this time working with collodion plates. In November of that year they obtained a photo of *Mizar* with its companion star, *Alcor,* which was sent to London for exhibition at the Royal Astronomical Society. This photograph had required an exposure of only 80 seconds with the 15-inch refractor.

III

Thus began the important art of celestial photography, which since that day has made possible the mapping of the heavens in a way undreamed of by previous astronomers. Young George Bond, whose enthusiasm was so largely responsible for the remarkable early results, forecast correctly the utility of photography in this field.

"Of the beauty and convenience of the method you will scarcely form a correct idea," he wrote to a friend, "without witnessing for yourself. On a fine night the amount of work

which can be accomplished, with entire exemption from the trouble, vexation and fatigue that seldom fail to attend upon ordinary observations, is astonishing. The plates, once secured, can be laid by for future study by daylight and at leisure. The record is there, with no room for doubt or mistake as to fidelity. . . . There is nothing extravagant in predicting a future application of photography to astronomy on a most magnificent scale."

The accuracy of that prophecy probably astonished even Bond, for he lived to see it carried out in part. It was not long before the pioneer work in celestial photography had been extended to every object visible in the heavens.

Even in 1845 Foucault, the man who later was to introduce the process of silvering glass mirrors for reflecting telescopes, began experiments with a view toward photographing that most brilliant of all celestial objects, the sun. Similar attempts were made about the same time by Fizeau, at Paris. In 1851 another experimenter, Berkowsky, scored a signal triumph by obtaining a picture of the sun's prominences at the time of a total eclipse.

But the most successful of the early sun-photographers was the same Warren de la Rue who had adapted the wet-plate process to the photography of the moon. For some time he had been experimenting with photographs of Jupiter and Saturn, but was disappointed when his photographs failed to show any planetary details. He then turned to the problem of photographing the sun, and in 1857 he was commissioned by the Royal Society to devise an instrument for sun photography to be placed in the Observatory at Kew.

The outcome of this commission was the construction of the first "photoheliograph." It was a small refracting telescope of 3½-inch aperture and a 50-inch focus. The plateholder was attached to the eyepiece, and was protected from the rays of the sun by a spring-driven slide at the front. This slide was capable of rapid motion, exposing the plate for only a fraction of a second—all that was necessary to record the brilliant image.

By means of this instrument the first solar pictures of scientific value were taken. With it a record of solar conditions was begun at Kew Observatory and continued for more than fifteen years.

Thus, one by one, the moon, sun, planets and stars were subjected to the scrutiny of the daguerreotype and wet plate. Finally, on September 3, 1880, Dr. Henry Draper of New York, son of that Dr. Draper who had been first to photograph a human face and first to obtain the portrait of the moon, turned his camera toward the most ephemeral subject in the celestial sphere, the shimmering, glimmering wispy light of a nebula, and succeeded in photographing it—the one in the constellation of Orion! Three years later the same nebula was photographed by Dr. Ainslee Common, English astronomer, with a 3-foot silver-on-glass reflector. After an exposure of only 37 minutes (an indication of how rapidly photography had advanced) he obtained a picture of the nebula so fine that it won him the Gold Medal of the Royal Astronomical Society.

Nor were comets neglected by enthusiastic astronomical photographers. In 1882 a very bright comet visited the neighborhood of the sun, and was clearly visible in the southern hemisphere. Dr. David Gill, director of the Royal Observatory at the Cape of Good Hope, strapped a camera in place of the eyepiece on the great equatorial telescope of the observatory, and succeeded in obtaining a good photograph. Not only was the comet clearly visible, but the stars in the field were also photographed, a circumstance that drew the attention of Dr. Gill to the desirability of making star maps by this method. This work he undertook at once, and thus began one of the first important photographic star-mapping projects of the southern hemisphere.

Finally, the camera was caused to lend itself to a more accurate measurement of the solar parallax at the transit of Venus of 1874. The leading English astronomers began to lay plans for observing this rare and historic phenomenon as early as 1870, and at the suggestion of de la Rue it was decided to let the camera supplement eye observations. A sum of money was raised for preliminary experiments, and Captain Sir William de Wiveleslie Abney, whose contributions to the art of photography as it relates to astronomy subsequently were of the

greatest importance, was placed in charge of this experimentation.

Captain Abney soon perceived that the wet-plate method would be completely out of the question for the fast, absorbing work of photographing the transit, and therefore turned his attention to the gelatine process, which at that time had only just been introduced. During the four years preceding the transit Captain Abney not only brought the dry-plate method to a state near perfection through his experiments, but he produced a special emulsion for sun photography which was considerably more sensitive to the red rays than any previous sensitive material, and which, in fact, was not improved upon in any important way in this respect until the introduction of neocyanin as a sensitizer in 1926.

IV

Now we must go back again to the early years of the nineteenth century and consider the development of another miraculous invention.

The story really begins in the year 1815, a year marked for momentous events in political history as well as science. In the United States the Congress had just ratified the treaty ending the War of 1812, opening up a new vista of peace and prosperity for the young country. In Europe the clouds of war were gathering. The opponents of Napoleon were preparing to give him a final defeat, which they did in June of 1815 at Waterloo.

Large as these things loom in the history books even today, neither was of as great ultimate importance, perhaps, as an event taking place quietly in a laboratory in Munich, where the young Fraunhofer, twenty-eight years old and already famous, was observing a puzzling phenomenon of light.

"In the window shutter of a darkened room," reported the young German afterward, "I made a narrow opening, . . . and through this I allowed sunlight to fall on a prism of flint glass which stood upon the theodolite. I wished to see if in the color

image from sunlight there was a bright band similar to that observed in the color-image of lamplight. But instead of this I saw with the telescope an almost countless number of strong and weak vertical lines.

"The relations of these lines and streaks among themselves appeared to be the same with every refracting substance; so that, for instance, one particular band is found in every case only in the blue; another is found only in the red; and one can, therefore, at once recognize which line he is observing. The strongest lines do not in any way mark the limits of the various colors; there is almost always the same color on both sides of a line, and the passage from one color into another cannot be noted."

What were those lines? What did they signify? Fraunhofer, greatest optician of his time, was never able to find the answer, tho many times it was almost within his grasp. He knew, however, that his work had revealed at least a part of something of tremendous importance. He tested light of many kinds, seeking for the answer to the puzzle. He tried the light of Venus, and of the star Sirius, of the moon and of flames.

"I have convinced myself by many experiments, and by varying the methods, that these lines and bands are due to the nature of sunlight, and do not arise from diffraction or illusion," he wrote. And again, later: "I have seen with certainty in the spectrum of Sirius three broad bands which appear to have no connection with those of sunlight; one of these bands is in the green, two are in the blue. In the spectra of other fixed stars of the first magnitude one can recognize bands; yet these stars, with respect to these bands, seem to differ among themselves. . . ."

He recognized that there were two kinds of bands: *bright* ones, which were invariably produced by light from flames and heated elements in his laboratory, and *dark* ones, like those he had seen in the spectrum of the sun and stars. He assigned letters to some of the most prominent bands, and was able to use them as references in measuring the distance and position of other lines. By this method he recognized that when sodium is

burned in the laboratory it produces two *bright* bands at exactly the same place in the spectrum as those occupied by two dark bands he had marked *D* in the spectrum of the sun.

Light bands, dark bands; and the same bands in all light from the same sources! In the light of Venus and the moon, he recognized unmistakably the bands of sunlight, weakened by losses due to reflection, but still there. But light from some of the stars, on the other hand, was different. What could it mean?

The same question puzzled many a good physicist after Fraunhofer, and had puzzled them before, for that matter. Fraunhofer was not the first to see the lines that now bear his name. As early as 1792 William Hyde Wollaston, a distinguished English physicist and chemist, and the discoverer of ultra-violet rays, noticed that when a beam of sunlight is admitted through a narrow slit and allowed to fall on a prism, the resulting band of colors will be crossed by a series of dark lines, as sharply defined as if drawn by a pen. Wollaston made the unfortunate guess that these lines merely marked the divisions in the colors of the band, and tho he expressed some curiosity, he never fathomed their secret or indeed experimented with them in any way likely to reveal their true nature.

Not so some of the men who followed Fraunhofer. More than a score of physicists at one time or another took up the investigation, puzzled over the Fraunhofer lines, and gave up in dismay. Forty-four years were to elapse before the genius of another German, this time the physicist Gustav Robert Kirchhoff, was to resolve the matter, revealing the secret of the spectrum in all its marvelous simplicity.

And what a revelation it was! What a revolution in scientific thought; what an extension in physical, chemical and astronomical knowledge was to follow it!

For Kirchhoff showed, in 1859, that Fraunhofer's lines, whether bright or dark, are keys to the identity of the chemical elements associated with the light producing them. When the light comes direct to the prism from a glowing gaseous element, the lines are bright, always in a certain position, and

always identify the element emitting the light. On the other hand, if a bright unlined light, such as that emitted by a solid incandescent body, passes through a gaseous element, the lines of the element will appear in the same place as before, but this time they will be dark lines, *for the element absorbs from the brighter body behind it exactly the same wave-lengths of light as those it emits when itself incandescent.*

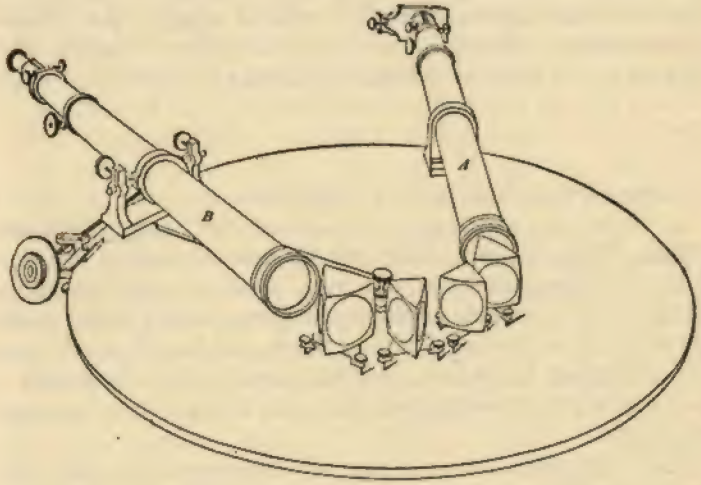


FIG. 23

Apparatus Employed by Kirchhoff in His Observations of the Spectrum of the Sun. A is the tube through which light was brought to the four prisms; B the instrument through which the spectrum was viewed.

Kirchhoff, working in the laboratory of the illustrious Robert Wilhelm Bunsen, and with the hot little gas burner which bears Bunsen's name and is still used in every well-equipped chemical and physical laboratory in the world, had observed that the dark lines in the D region of the spectrum of the sun could be changed to bright lines by bringing a flame colored by sodium vapor in front of the slit. Conversely, he found that by placing an exceedingly brilliant unlined light, such as that from the oxy-

hydrogen limelight, behind the sodium flame, he could change the bright sodium lines to dark lines at will!

Thus, the two bright lines which Fraunhofer marked *D* in the solar spectrum reveal that there is sodium in the outer envelope of the sun!

Thanks to this discovery of Kirchhoff's, astronomers aided by a piece of glass of proper shape, a telescope and an eyepiece, could now subject the sun to chemical analysis; more, even the stars and nebulæ, the tails of comets, the brilliant emanations of meteors, the luminous silvery matter afloat vaguely in the galaxy—everything in the universe that glows!

V

Nor were they long setting about it.

In his private observatory in London, the young astronomer William Huggins, who later was to become one of the best-known of astronomical adventurers, fitted a prism in proper position into an 8-inch refracting telescope made for him by the American telescope-maker, Alvan Clark, and less than two years after Kirchhoff had announced his marvelous interpretation of the meaning of Fraunhofer's lines, he analyzed the spectrum of a star.

Thus the genius of an American telescope-maker, the brilliance of a German physicist, and the technical skill of an English astronomer were combined to bring a star into the laboratory and examine it. Even in this day of commonplace wonders it is not difficult to imagine the awe and excitement with which Huggins, later to become Sir William Huggins, beheld his first stellar spectrum and perceived that the stars and sun, as had long been suspected, were made of similar materials. It was a final proof that the universe was chemically a unit; that elements found on earth were also to be found in the stars, the sun, and in all other celestial bodies—that tho man himself is made of dust, at least it is star dust!

Of course Huggins was not the first man to inspect the spectrum of a star; Fraunhofer had done that in his long, fruitless

search for the meaning of the phenomenon that bears his name. But Huggins was the first to perceive the spectrum of a star and know what he was seeing; to know that the messengers of light crossing millions of miles of cold space were telling him the names and nature of the elements of star-stuff.

Presently they were to tell him still more. Huggins reported his first striking discoveries before the Royal Society in the year 1863, in a paper soberly entitled "Lines of Some of the Fixed Stars." In the same year he made another great imaginative leap. He perceived how remarkably the camera and the spectroscope could be combined, and even tried to bring about the wedding of these two instruments. But only the old collodion method of photography was then available, and tho he succeeded in obtaining some blurry marks on his plates, they could hardly be called spectrum photographs, since they were of no scientific value.

Relief fortunately was not long in coming. In 1875, the new gelatine plate method of photography having appeared, he solved the problem, and actually was the first to use the *spectrograph,* or photographic spectroscope, with success.

With that combination, what a vast field of new star knowledge he opened up! Today the spectrographic telescope is the chief instrument of the new branch of science, *astrophysics,* the physics of the stars. It is the interstellar detective that tells us secrets undreamed of by the imaginative Huggins or the venturous-minded Herschel—stories of double stars too far away or too close together to be resolved by the telescope alone; stories of swift radial or line-of-sight motions of stars, clusters and nebulæ. It tells us the age of the stars; of their slow death and possible rebirth, and of many another marvel.

How does the spectrograph reveal these things? That is a long and complicated story, and must be reserved for a later chapter of this book.

PART II

THE INSTRUMENTS THAT EXPLORE THE STARS

Chapter VIII

MODERN TELESCOPES—HOW THEY WORK AND HOW THEY ARE MOUNTED

I

NOW comes a most fascinating matter: the explanation of how two or three pieces of glass can be made to bring us messages from the far regions of space; can be made to see for us better than our eyes, to weigh the stars and tell us their chemical composition, to reveal something of their life histories, their ages, their pasts and futures, and disclose the vast rushing clouds of suns toward the outer reaches of space.

What would the astronomers of old say if they could see the great observatories of today? Would they recognize any of the instruments as descendants of the temperamental contrivances with which they worked?

It is likely that there would be no confusion about the great refracting telescopes such as those at Yerkes and Lick Observatories. These instruments resemble the telescopes in use in the early part of the nineteenth and most of the eighteenth centuries. The major point of difference is their size, and this would hardly puzzle astronomers who had heard of, or used, the instruments made by Hevelius, Huygens or Campani.

But would even Newton recognize the modern reflecting telescope as a relative of the tiny model he made for the Royal Society? Would he, as a matter of fact, perceive the kinship of these squat open-work giants with telescopes at all?

More likely he would feel, as many visitors to modern observ-

atories do, that these are weird engines left by some alien race—implements, for instance, like those brought to earth by the Martians of Wells's *The War of the Worlds*—not mirrors for the stars.

Where, for instance, does an observer look into them? This is a question many visitors ask, and a natural one, for in such a maze of apparatus the eyepiece is often hard to find. Look, for example, at Plate 24, which shows an observer at the eyepiece of the Cassegrain focus of the 100-inch telescope at Mt. Wilson Observatory. How insignificant are both the eyepiece and the observer in this jungle of metal!

Another thing that gives a modern reflector an appearance unlike the popular conception of a telescope is the open-work tube in which the mirror is housed. The reason is that there is no need for a closed tube; to close it up would add greatly both to the cost and the weight of the instrument.

In large *refractors* closed tubes are used, just as in the earliest telescopes, and for the same reason. The greatest weight in the optical part of such a telescope is that of the object-glass, which must be held at the outer end of the tube with perfect rigidity. This can best be accomplished with a closed tube. The tube also is useful in the refractor to screen off any side-light that might enter from the room in which the telescope is used. Its effectiveness in this respect is furthered by coating the interior with a black, light-absorbing paint and equipping it with internal diaphragms which serve, somewhat as did the circular diaphragms in old Hevelius's 150-foot telescope, to stop all light except that moving toward the focus.

But in a reflecting telescope there is no focus until the light has once traversed the length of the tube and impinged upon the mirror; hence there is no necessity of stopping any coming in a direction parallel with the axis of the tube. As for light from the room, this will cause little disturbance. Moreover, since telescopes are used in darkness, the best possible material for absorbing such stray light is the velvet black air of the observatory at night.

II

The matter of the location of the eyepiece is worth returning to for a moment, because it illustrates not only a great difference in the telescopes of today, but also a great change in the practises of astronomy.

The popular conception of an astronomer is of a man who works tirelessly all night, his eye glued to an eyepiece, sweeping the heavens with his glass. Thanks to the photographic plate, his task is very different now. Many astronomers work in the daytime, as well as night, a major part of their work being the examination and measurement of plates which were exposed the night before or at some time previously. The photographic plate has almost wholly taken the place of the eye at the observer's end of the telescope.

The eyepiece consequently is used only in adjusting the telescope, in making sure that it is properly directed, or possibly in some special piece of investigation where visual observation is desirable or necessary. For the most part an astronomer does not look through the eyepiece of his telescope from one month to another; it is usually not necessary to do so even when getting ready for a night's work. Practically all telescopes can be directed accurately by the setting circles with which they are provided. It is necessary only to swing the instrument to the proper point in right ascension and declination, and finally bring it to bear exactly on the desired object with the aid of a finder.

In large refracting telescopes the eyepiece is replaced by the photographic plateholder or the spectrograph (Plate 25). In the reflectors the plate or spectrograph may be located at one of several points; either at the main focus (which is usually preferred) or at the Cassegrain focus. In the case of such an instrument as the 100-inch telescope, which has a "coude" or modified Cassegrain focus, the plate or instrument may be located in another room, such as in a temperature-controlled chamber below and to the south of the instrument.

III

In earlier chapters we have seen that all telescopes are of two general types, classified as to whether a lens or mirror serves as the principal gatherer of light. Tho in former days there was much rivalry between the two kinds, and much debate as to which was the better, modern astronomy would be much poorer in data today were not both refracting and reflecting telescopes available. Each has special capabilities and functions in modern research that cannot well be served by the other.

From these general types are derived whole families of special telescopes, each designed and mounted in such a way as to do a specific kind of work well.

The modern counterpart of the long telescope with which Bradley noted the aberration of light, for instance, is the transit telescope, used in all large observatories to tell the time by means of the stars, to observe the stars for parallax, and to give the true position of stars for charting the heavens by visual methods (Plate 23). Transit telescopes are refractors, so mounted that they can be moved in altitude, or along the meridian line, but not in azimuth, or from side to side. This arrangement provides a simple and accurate method of learning exactly when stars cross the meridian, hence their precise position in right ascension and declination.

Another specialized kind of instrument is the photographic telescope—a refractor in which the objective is specially corrected to bring to focus the violet and ultra-violet photographic rays. Such telescopes are never used with the eye, but always with the photographic plate. Usually they are joined to a second telescope, corrected for the visual rays, which is used as a finder and guide. One such telescope, recently completed for the United States Naval Observatory, consists of three instruments: a small one for a field finder; a second, larger instrument for visual guiding of the instrument when in use, and the photographic telescope itself (Plate 22). The main instrument of such a combination, of course, has no eyepiece, for it would be useless. The photographic plate is held directly at the focus of the object glass.

Specialization is by no means limited to refractors. The new Ritchey-Chrétien reflector at the United States Naval Observatory (Plate 22) is an excellent example of mirror-telescope construction for a special use. It is a photographic reflector, in which the two curved mirrors (it is used as a Cassegrain) are figured specifically to provide a wide, clear field for the photographic plate.

These are typical cases of specialization, but for that matter most large telescopes today are designed for some specific use. The great reflectors are relatively at a disadvantage in studying the planets, for example, but are unrivaled for the distances they "see" into space and the wealth of luminous objects they detect and bring back to us. The great refractors such as those at Yerkes and Lick Observatories on the other hand are unmatched in their resolving power, in the planetary and lunar detail they reveal, in the way they lend themselves to studies of double stars and to certain kinds of spectrographic work.

Hence, there is no longer any real rivalry between the two chief types of telescopes. Some astronomers have their preferences, which is only natural, but no one today argues seriously about the relative merits of reflecting and refracting telescopes. It is altogether a matter of determining the fields for which each is best fitted, and of supplementing the work of one with that of the other to get the most complete information about all bodies under observation.

IV

The major difference in appearance between the great telescopes of today is due not so much to the nature of the optical parts as to the *mounting.* This includes the whole of the apparatus by which the telescope is held in place and permitted to swing to the various portions of the heavens.

The importance of a proper, smooth-working and well-contrived mounting is apparent even in the case of small tele-

scopes. Only instruments small as a mariner's spy-glass require no mounting at all. Telescopes that weigh anywhere from a few-score pounds up to several tons present a mounting problem as varied as are telescope designs and uses. There is only one constant factor: as the weight grows, the problems of mounting design grow with it.

The need for suitable instrumental mounting is more ancient than the telescope. It was a serious matter with Tycho Brahe, who passed much time devising the right kind of pivots for his weighty quadrants, sextants and armillary spheres. The great Arabian astronomers before him had met the problem. Even the Chinese designed ingenious mountings, some surprisingly modern, for the contrivances used in their astronomical research.

The coming of the telescope brought the matter to the fore in a new way. Even the smallest telescopes produce magnification of the image; they magnify not only its size but also any apparent motion in it. A poorly mounted telescope, even tho the pivot on which it turns is smooth and easy so far as the eye or hand can perceive, will produce a distorted or jumping image.

Again, the telescope enlarges a small field of stars, and hence magnifies the apparent progress of this field from east to west. The telescope must be so mounted that it can keep up with the movement smoothly, holding the objects always centered in the field. This will be possible only when the mounting is smooth and absolutely rigid, and when it includes some kind of device by which it may be moved steadily and a little at a time in either of the two directions of space—in *altitude*, (up and down), and in *azimuth* (right and left).

The simplest mounting therefore will require a double pivot, one permitting motion in azimuth, the other in altitude. This is called the *altazimuth* type, and is often seen on small telescopes of the portable, tripod variety (Fig. 24).

In the better altazimuth mounts the instrument is supplied with "slow motions"—devices by the use of which the operator can adjust his instrument slowly and accurately to follow the

movement of a celestial body across the sky. These are usually in the form of fine screws, sometimes with flexible cords or springs attached so that they will come handily within reach of an observer at the eyepiece. A fine, slow movement is produced when they are turned. Separate slow motions are provided, of course, for altitude and azimuth.

The altazimuth mounting is not only a simple one, but it is useful, even for larger instruments, where photography is not involved. It must be remembered that William Herschel used no other kind, even for his largest reflector, and with such a mounting was able to accomplish a large part of the colossal survey of the heavens which he undertook. Other astronomers before and since have found the altazimuth mounting satisfactory for visual work. But photographic astronomy cannot be carried on with an altazimuth, and the reason is easy to understand.

The vantage place of an astronomer is always some point on a sphere, the earth, which is in continual rotation on its axis. This rotation is what makes the stars appear to move across the sky from east to west, but they do not, except to observers directly on the equator, appear to follow a straight-line path. The course is curved, the curvature depending on the latitude of the place from which they are observed.

At the equator, as we have noted, the path of the stars will be a straight line from east to west. At the poles, on the other hand, it will be a circular path in azimuth. Between these points the stars will pursue a course which deviates from the straight one of the equatorial stars and the azimuthal path of the polar ones exactly

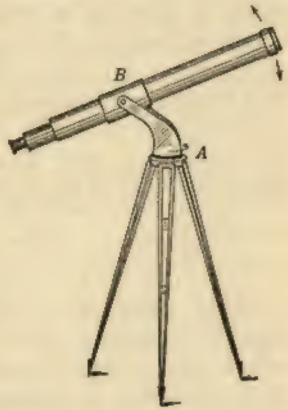


FIG. 24

Simple Altazimuth Mounting. The telescope can be adjusted in azimuth at A and in altitude (declination) at B.

in proportion to the distance north or south of the equator at which they are observed.

At any one of these intermediate points an observer will need to make constant adjustments with his altazimuth telescope, moving the instrument both in altitude and azimuth, to follow a star. The coordination of two such adjustments with great accuracy is difficult, and even momentary failure may ruin the photographic plate. Hence some kind of mounting must be devised which will follow the stars exactly across the heavens, with no other adjustment than that necessary to keep up with the rotation of the earth.

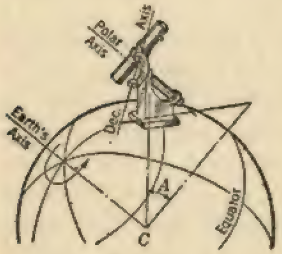


FIG. 25
How an equatorial mounting permits a telescope to follow the stars.

Such a mounting is the polar, or *equatorial*—first used for telescopes by Christopher Scheiner. The principle of this type of mounting, now seen in all large telescopes, is shown in Fig. 25. In effect the azimuthal axis is tilted up to coincide in direction with the axis of the earth. Then, once the instrument has been brought to bear on a star, it can follow continuously with the aid of a single adjustment. Because of its regularity, this movement can be handily supplied by a clock set to keep sidereal or star time.

V

Many variations of the equatorial mounting are in use on modern telescopes. One of the simplest is the "German" type, often used in light telescopes and in refractors, and attributed to Fraunhofer. It requires but a single pillar, to which is affixed the polar axis. Turning on this is the altitude or declination axis, like the short arm of a capital T. At one end of the altitude axis the telescope is fastened; at the other is a counterweight. Both the Lick and Yerkes refractors are mounted in this manner (see Plate 14).

For heavier telescopes the use of a second pillar to support the polar axis may be desirable. This form is usually known as the "English" mounting, and is to be seen in the 72-inch reflecting telescope of the Dominion Astrophysical Observatory (Plate 20), the new 36-inch reflector at Greenwich Observatory, and many others. In this type the declination axis crosses the polar axis, bearing the telescope at one end and a counterweight at the other.

The English form is quite useful for heavy instruments because there is less danger of bending or flexure of the parts, but it is also attended by certain difficulties, notably the shutting off of part of the sky by the high northern pillar of the mount. While this is indeed a drawback, most large telescopes until quite recently have been thus mounted because of the other manifest advantages.

The 100-inch telescope at Mt. Wilson Observatory, second largest now in existence, has a variant of the English type, known as the yoke mount (Plate 15). In this mounting the polar axis consists of a double bar, joined at the ends to form the bearings, and separated for most of the length sufficiently to admit the end of the telescope. The instrument is mounted between the bars, the declination axis being the pivot on which it turns.

In the Hooker telescope a further refinement is introduced, in that the bearings at either end of the polar axis consist of troughs of mercury, upon which the weight of the telescope (more than 100 tons), is floated. Rotation of the axis is practically frictionless.

Still another type which belongs to the general group of English mountings is the "fork." Its derivation from the yoke idea is strongly suggested. The telescope is firmly grasped between the fingers of a fork and held to the northward of a massive bearing capable of supporting the whole mount. Such a mounting is used in the 60-inch telescope at Mt. Wilson (Plate 24), in the Ritchey-Chrétien telescope of the United States Naval Observatory (Plate 22), and in many others. At one

time a fork-type mounting was earnestly considered for the 200-inch Mt. Palomar telescope.

This kind of mounting has several special and important advantages. In the first place, it overcomes the objection to the standard two-pillar English mounting, in that clear access to the sky is given the telescope to the northward, practically down to the horizon, while to the south there is no obstacle beyond the comparatively low southern bearing. It places the telescope out in the clear, where access may be had from three sides. It offers no hindrance to removal of the mirror for resilvering or other repair.

It was such a mounting, with variations, that Lord Rosse used for his great 6-foot mirror. Dr. Ainslee Common, famous English telescope-maker of forty years ago, used it for his 36-inch and 60-inch silver-on-glass telescopes, the former of which is now in use at Lick Observatory and known as the Crossley Reflector. The fork-type mounting was long a favorite with Dr. George W. Ritchey, one of the foremost modern telescope-makers, and was used by him in mounting several instruments which he designed, including the 60-inch at Mt. Wilson and the special 40-inch that bears his name at Washington. Such a fork-type mounting, as embodied in the 60-inch reflector at Mt. Wilson, is shown in Plate 24.

VI

We cannot leave this subject without considering for a moment those curious telescopes which are a part of their own mountings, so to speak, and which for special purposes are sometimes more useful and often more convenient than the more conventional types. In a sense telescopes of this sort represent a modern contribution to fundamental instrument design.

Let us consider, for the moment, the plight of an observer forced to use his telescope in a cold climate, as on a mountain top or in wintry northern regions. The ordinary instrument condemns such a man to share the elements with it, for so

sensitive is the lens or mirror of a good telescope that the whole instrument must be brought to the same temperature as the surrounding air before it can be used. In observatory domes (which naturally are not heated) this means opening up on frosty nights, and waiting for the room to become thoroughly cold before work can begin.

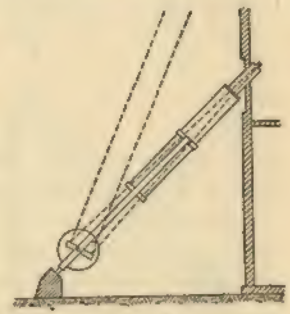


Fig. 26

Scheme of the Gerrish Polar Telescope at Harvard Observatory. The eyepiece is in the second story room of the building; the tube of the telescope is the polar axis.

Unless the observer is supplied with a telescope especially constructed with this matter in mind, observation must go on under extremely uncomfortable conditions at times, even at the best of observatories. The only way to prevent it is an instrument arranged in such a way that the observer can remain indoors where it is warm, while the telescope goes outside.

Such a forth-faring instrument was designed by Sir Howard Grubb, English telescope-maker, and installed in the Crawford Observatory, Cork, Ireland, about 1880. Grubb hit upon the idea of making the main tube of the telescope and the polar axis one and the same, so that to keep up with the stars the telescope need not have any angular motion, but merely rotate, the light of the sky being brought to it by a movable mirror.

This contrivance was permanently mounted on a small truck which ran along a track. When an observer had use for it, he wheeled the instrument to a window at the south side of the observatory, and pushed it out on a balcony. There it moved into place in such a fashion that when the window was closed the instrument stood outside, but the eyepiece projected through, and was inside.

A better application of the same general idea is to be seen in the 12-inch "polar telescope" designed by W. P. Gerrish and set up more than thirty years ago at Harvard Observatory

(Fig. 26). It has been in use regularly since that time, and has proved to be a convenient instrument.

The Gerrish telescope differs from Grubb's in that it is permanently mounted, but like the earlier design the telescope itself forms the polar axis of the mount. The eyepiece end is comfortably housed in the second floor of the main observatory building, on the south side. The other end, bearing the objective and the reflecting mirror, is grasped by a metal framework which in turn is pivoted on a concrete pier set firmly in the ground. Controls, including a contrivance to move the mirror when focusing the telescope on a new object, are located in the upper room, near the eyepiece.

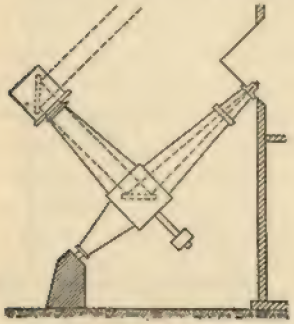


Fig. 27

Scheme of the Equatorial Coudé, a type of fixed-eyepiece telescope with a wide field of view, but obtained at the expense of a double reflection.

These ingenious devices and their kind have serious limitations, chief of which is the restricted portion of the heavens viewable through them. Northward the field is cut off near the zenith by the building in which the eyepiece is located. Southward it is restricted by the capacity of the small movable mirror to send the light into the objective.

These difficulties can be overcome as a matter of fact only by resorting to two reflections instead of one. A double reflection telescope was constructed for the Paris Observatory in 1882, in the style known as an *equatorial coudé*. At first glance this instrument looks like an English equatorial mounting without its telescope. The telescope, however, is *inside* the mounting (Fig. 27).

An eyepiece in the polar axis brings the image comfortably inside the second-story room of the observatory. At the point of intersection of the polar and declination axes a 45-degree mirror throws the rays from the objective into focus at the eyepiece.

The objective itself is at the end of the declination axis, and is so mounted that a second mirror, this one movable, can bring the light into it from practically any position in the heavens except low in the north, where a limit definitely is set by the height of the building.

VII

It may be objected that telescopes such as these are of little practical value in an age of photography. Today it is no longer necessary for the astronomer to brave the cold; the sensitized plate can do it for him. This is partly true, but there is nevertheless a use for the principles represented in these polar telescopes. One important outcome of such experiments is to be found in the permanent-position telescopes of Mt. Wilson Observatory, which borrow somewhat from both the polar telescope and the equatorial coudé.

One of these, and the earliest, is the famous Snow horizontal telescope, designed by George W. Ritchey for the study of the sun. It consists of a long box, elevated slightly at the open end, and containing a concave mirror like that of an ordinary reflecting telescope, which receives and concentrates the rays of the sun, passing them into a spectrograph, spectroheliograph or any other instrument which the investigators desire to use in connection with it.

The interesting part is how the rays get into the box. This is accomplished through the agency of two plane mirrors mounted outside, one on a small movable equatorial mounting, the other fixed. Such a combination is now known as a

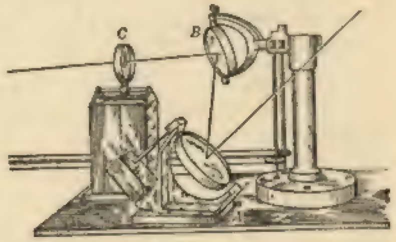


Fig. 28

How the Cœlostat Mirrors Make the Heavens Stand Still. The mirror A, mounted equatorially, turns half as fast as the earth, thus keeping the beams of the stars playing on the fixed mirror B at the proper angle to pass them through the lens C.

cœlostat, because it can literally make the heavens stand still (Fig. 28). The equatorial mirror moves on its axis exactly half as fast as the stars seem to move in the sky. The light is reflected to the second mirror, which in turn passes it to the large speculum inside the horizontal telescope. When the moving mirror has been brought to bear on the sun, its light pours into the telescope all day long, a steady beam. The astronomers at work with their instruments need give no thought whatever to the sun's actual position in the sky. As far as they are concerned it is as motionless as on that day, long ago, when Joshua commanded the sun to stand still.

The tall, graceful tower telescopes are in effect horizontal telescopes standing on end—in this case the laboratory end. The two magical mirrors of the cœlostat are located at the top, under the movable dome; the telescope lower down. At the bottom, in a pit half as deep in the earth as the tower is tall above it, is the controlled-temperature laboratory where the sun's rays are photographed, analyzed and examined.

Chapter IX

SOMETHING ABOUT LIGHT AND HOW THE TELESCOPE MAKES USE OF IT

I

IT is time now to inquire about the connection between the telescope and the stars—that substance, whether fluid, solid, streams of infinitesimal particles, disturbances in an ether or otherwise, which brings us messages from the stars and reveals to us their positions, states of chemical and physical being, motions and other characteristics.

Fortunately we shall not have to define light in making such a study, nor shall we have to try to reconcile the several theories of its nature which confound the student and bewilder the scientist. For our purposes the old classical theory—that light is a wave-like disturbance in some all-pervading medium such as the ether—is enough to explain its optical behavior.

This theory is convenient for several reasons: one is that it makes possible the comparison of light phenomena with other types of wave motion; hence we can construct "models" of the light action under discussion and dispense almost entirely (in a fragmentary consideration such as this) with troublesome mathematical symbols. Moreover, the wave theory explains in every detail the *optical* behavior of light; it is only when the scientist tries to explain the origin and emission of light that it breaks down, and that is a branch of physics with which we are not now concerned.

Let us begin by considering the motion of small ripples in a shallow pan of water. These ripples are often so tiny that it is difficult to see them, but if we place the pan of water in such a position that a beam of sunlight falls upon it at an

angle, and is reflected upward to a screen, we shall see the ripple motion on the screen in detail as the sunlight is scattered and reflected by the various parts of the moving waves.

We strike one end of the pan. Immediately a train of ripples starts for the other end. In a moment they reach it, start back again, and *pass through* the trains of waves still coming from the original source (if we have continued to strike the pan) without in ordinary cases disturbing them.

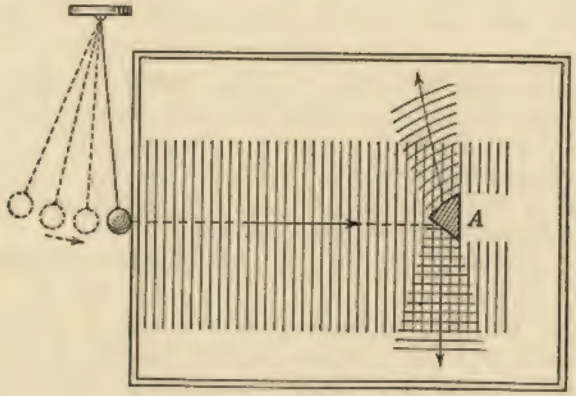


FIG. 29
The reflection of waves from the surfaces of a small irregular object A, as shown by water waves in a shallow pan.

Now if we place a small object in the pan, somewhere between the wave-source end and the other, small portions of the waves will strike this object and be scattered in all directions except behind the small object (Fig. 29). The intensity of the scattering, or rather, the amount of energy transmitted by the new waves in any one direction, will depend on the shape of the object. If it is perfectly round, circular waves will be given out; if it is square, straight waves will be reflected off one or more of the faces, depending on its position.

This is the fundamental phenomenon of light that we witness every day. We see objects of two kinds: those that give out

light, and those that reflect it. We are aware that the source of light in the daytime is the sun, and that all we see on earth are the shapes of things as indicated by the way in which they reflect the sun's light to our eyes.

The same is true of celestial objects. The sun and stars give off light; hence we see them directly by their own radiance. Celestial objects of the other class are viewed by reflected light. These include the moon, planets, the satellites of the planets, the planetoids. Comets represent a combination of the two. They emit light of their own when they have approached close enough to the sun to become heated up; they also reflect sunlight, so that in the light of a bright comet the spectroscope will produce the typical dark bands of reflected sunlight, and the bright bands of emitted light as well.

II

The eye is an optical instrument; in fact, the generic name for such instruments is derived from a Greek word meaning "sight."

In this remarkable instrument light enters through a space called the pupil in such a manner that it must pass through three different kinds of substances before it reaches the sensitive rear wall of the eye, or the retina. These substances are, in the order in which light traverses them, the aqueous humor, the crystalline lens, and the vitreous humor.

The secret of this camera-like arrangement is that light, in passing through various substances, is slowed down, the amount of slowing depending on the nature of the substance. Slowing produces what is known as refraction, which can be defined simply as the bending of rays of light when they pass obliquely through a transparent substance in which their speed is greater or less than in the medium in which they formerly were traveling.

This bending makes a stick appear broken at the water-line when it is thrust obliquely into a pool. Other instances of it are common to our experience. The explanation is perfectly

clear and simple if consideration is given to the necessary reaction which a train of waves would experience upon striking at an angle a substance which slowed them down. The end of each wave striking the surface first is retarded before the rest. This results in a wheeling motion, changing the direction of the line of advance in proportion to the difference between the ease of movement in the former medium and in the latter one (Fig. 30).

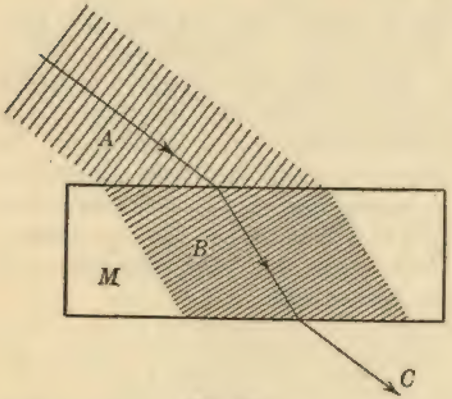


FIG. 30
How Light Is Bent, or Refracted, in a medium M in which its velocity is changed. A is the entering beam, C the direction of the emerging beam.

Sir William Bragg, in his excellent book, *The Universe of Light* (Macmillan), points out that the same phenomenon is noticeable when a column of soldiers marching in squads or platoons comes upon a plowed field or other sharply defined area where the walking is harder. If the column strikes obliquely the men who first reach the plowed field are slowed down. Their companions pass them at the old rate of march until they, too, strike the roughened going. Finally, by the time the last of the rank has reached the plowed field the entire line of march has unconsciously been altered.

In a lens, such as that presented by the eye pupil, we are not dealing with a rectangular surface such as a plowed field, but with a curved one. When the slowing down occurs in this case it has a curious and important result. Whereas, in the rectangular surface, a simple bending of the straight line to a new direction occurred, in a properly curved structure a *con-*

vergence of the rays will be seen. This is the secret of the lens.

Let us assume that the lines L (Fig. 31) represent wave-fronts of light approaching the double convex lens A, made of a refracting substance different from the medium, such as air, through which the light is traveling at L. Suppose also that the material of A considerably slows down the passage of the light. Then as the first wave-crest approaches it will strike A first at its middle, and this section will be slowed first, while the ends of the wave will proceed as usual, and will thus be bent into a curve. This curve has already become pronounced by the time all of the first wave has entered the lens, but again, the ends of the wave are free of the lens on the emerging side sooner than the center. This increases the curve still more. The speeding ends of the wave, instead of proceeding in their original direction, have now been given a pronounced inward motion.

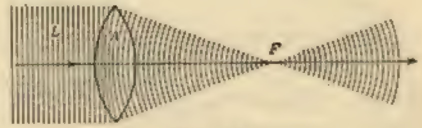


FIG. 31
How a beam of light is brought to a focus by a convex lens.

When produced by a properly constructed lens, the inward slant is such as to cause the ends, and indeed the entire wave, to pass through a single point F, called the focus. After the focus has been passed the several parts, following their various motions, diverge again. But now the part of the wave which had been on the right at L diverges toward the *left*, and the part that had been on the left goes off toward the right. Thus the beam of light, which consists of a long train of such waves, has not only been made to converge to a point, but it has been twisted completely around, or more exactly, turned inside out.

III

Convergence accounts for the concentration of energy observed at the focus of a lens, but we have still to explain that important phenomenon, the production of an image.

When an object is viewed by reflected light we see not one beam, but many. Each point of the object is sending out its own rays of reflected light, the relative intensity, color and other factors of which depend on the nature of the light which it is reflecting, and the capacity of the object to reflect or absorb such light.

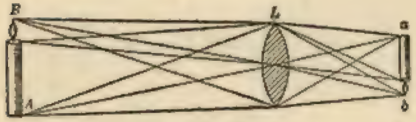


FIG. 32

How an Image is Formed by a Convex Lens. Light from every point of the object AB falls on every part of the lens, and the several beams are brought to focus at appropriate points in the plane ba.

The countless numbers of beams reflected from such an object will vary in intensity and color according to patterns which the many parts of the reflecting object have stamped upon them. When a lens is placed to catch these reflected beams it will produce a convergence of all of them, just as in the case of a single, simple beam in Fig. 31. But these beams cannot all converge in the same point, for unless the object is enormously distant, the incoming beams cannot all strike the lens at exactly the same angle.

What happens is shown in Fig. 32. Here the object *AB* sends beams which pass through the convex lens *L*. Since the light is not sent out in any certain direction from the various points of *AB*, the lens *L* will receive on its whole face beams from each point of the object. The divergent beams arising from any given point will be caused to converge again to an appropriate point on the other side of the lens, and thus an image is built up at *ba*. This image will be inverted. Its size will depend on the focal length of the lens and the distance from the lens of the object *AB*.

The focal length of the lens will depend, in turn, upon the curvature of its surfaces, and is usually considered as the point at which parallel beams, such as those coming from a light source at great distance, are brought to a focus. This is called the focal point, or in the case of telescope and microscope objectives, the main focus. The image will not necessarily be formed at that point, for if the light from an object comes from so close at hand that its rays are sensibly *not* parallel, as we have seen above, the actual focal length or the plane at which the image will be formed will depend upon both the curvature of the lens and the distance of the object.

Some of these matters can be demonstrated readily with a simple reading or burning glass. The focal length may be found by allowing the rays of the sun to fall upon it, measuring the distance at which the most intense concentration of light appears behind it—the point at which burning, if the glass is used for that purpose, takes place most briskly. This *burning* focal length will actually be a little farther from the lens than the focal point for light, but for the purposes of the demonstration the slight discrepancy may safely be ignored.

Now, having determined the focal length of the lens, place a candle or electric lamp in a dark room as indicated in Fig. 32, and cast its image through the glass upon a sheet of white paper. It will be observed that both the size of the image and its distance from the lens vary according to the distance of the object from the lens. As the glass is drawn away the paper screen must be moved up to produce a sharply defined image.

It is this situation—the changing location of the image for different distances—that makes it necessary to adjust a camera or binoculars in order to focus sharply the images of near and far objects.

It is also necessary to adjust the eye, as when we "screw up" our eyes to view an object very near, or strain them to make out details at a great distance. The eye is a device essentially like our reading glass and sheet of white paper. The crystalline lens is analogous to the glass, the retina to the paper screen. But adjustment for near and far vision in the eye is made not by changing the distance of the retina from the lens, but by changing the curvature of the lens itself; a type of adjustment possible with such flexible material as that of the crystalline lens, but of course out of the question with a lens of glass.

IV

Light enters a refracting telescope just as it does the eye, through the convex lens known as the objective. This lens converges the light to a focus, and there forms an image of the object which emitted or reflected the light.

Now, to make the image equal in size to the object under observation, it would be necessary, as we have seen, to use an objective the focal length of which is exactly equal to the distance from the object to the objective. Since this is impossible except for very near objects, the image formed at the main focus of a telescope will always be smaller than the actual object. Its real size will depend upon the focal length of the objective. The longer the focus, the larger the image.

Tho the image in the main focus of a telescope will always be small, if it is desirable to enlarge it we may have recourse to magnification. In all visual telescopes the image cast by the objective is magnified by a second lens or series of lenses (the eyepiece), in order that it will appear larger and its finer details be revealed.

Magnification depends upon the fact that the larger the image cast on the retina, the clearer will its details be, provided all parts are focused sharply. When examining a small object with the unaided eye, we seek to enlarge the retinal image by bringing the object closer, but there is a limit to which this can be done. When the object is brought nearer than a certain point the image gets bigger, but the details are lost, due to the inability of the eye to adjust itself sufficiently to bring them into sharp focus.

The eye can be aided by the interposition of a lens between the object and the pupil. The lens, by supplementing that of the eye, makes it possible for the latter to cast a sharp, enlarged image on the retina without the necessity of adjusting the crystalline lens beyond its useful capacity. As shown in Fig. 33, a single convex eyepiece lens, properly placed, catches the diverging rays of light after they have passed the main focus of the telescope, and reconverges them. They would, presently,

form another image in the focus of the second lens, but the lens of the eye is interposed inside the focus of the eyepiece lens, in such a way that the rays passing through both lenses are brought to focus on the retina.

Of course there are natural limits to magnification. The question of the amount of light available is one important limiting factor. Obviously the eyepiece and the eye-lens will have to make the enlarged retinal image with only so much light as the objective is able to gather—will have to make it with *less*, in fact, due to the slight but important losses of light along the line as it passes through the lens system. Consequently, as the retinal image increases in size, the illumination upon it will decrease, until a point is reached at which no further details can be revealed by further increase in size.

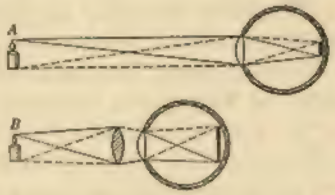


FIG. 33

How the Eyepiece of a Telescope Magnifies an Image. A, the image viewed with the unaided eye. B, the convex lens permits the eye to be brought closer, enlarging the image on the retina.

V

So far we have considered light as consisting of simple equidistant trains of waves, all responding in exactly the same way to each situation presented. What we know as *white* light actually consists of bundles of waves which differ from each other in the amount of energy they represent. The difference in energy is expressed in the length of the waves—that is, in the distance from one wave-crest to the next. Those of higher energy are shorter; those of relatively less energy are farther apart; the difference being roughly analogous to the large swells of the comparatively calm sea, and the short, choppy waves lashed up by the fury of a storm.

The long waves do not interfere with the short ones, any more than a train of water waves going in one direction inter-

feres with or impedes the progress of a train going across its path in another. The long and short waves have something in common—their velocity. Long, short or intermediate, all traverse the transmitting medium at the same speed.

But when it comes to changing obliquely from one transmitting medium to another of different refracting power, it is a different story. To this situation the different waves of visible light, as well as the infra-red on the longer side of the visible band, and the ultra-violet on the shorter, respond somewhat differently. If a beam of white light is passed through a prism, for instance, the different wave-lengths of light will take different paths. When the beam emerges, the various waves, instead of all being mixed together as before, will appear neatly sorted and laid side by side in a band of light which we perceive as a color spectrum; the blue at one end, the red at the other, the intermediate colors spread between in the order of their wave-lengths.

A similar action takes place in a simple lens, which is unable, in the nature of things, to converge all the kinds of light into a single point. The focal point of blue and ultra-violet light will be nearer the lens than the focal point for the bright intermediate portion of the spectrum; that of the red and infra-red farther from it. There will therefore be as many foci as there are varieties of waves in the original beam (Fig. 11, page 46).

This is the cause of the mysterious colored ring visible around the image in a non-achromatic telescope, and was one of the reasons, as we have seen, for the invention of the reflecting telescope. We have also seen that chromatic aberration substantially can be overcome, as Chester Moor Hall and the Dollonds demonstrated, by a proper combination of refracting media in the objective—in practise a multiple lens of crown and flint glass.

Color aberration is overcome in this way because refraction and color separation are not proportional to each other in all substances. Each transparent medium has its own refraction index and color dispersion index. By combining two substances of proper kind in lenses of correct shape, the tendency of one

to separate the colors may be substantially neutralized by the other.

It is necessary to qualify this statement, because actually no simple combinations will produce absolute achromatism. The best that can be done is to correct the telescope for the rays most needed—the green and yellow for visual work, the blue and ultra-violet for photographic purposes, and so on.

VI

In the mirror telescope an entirely different kind of light-behavior comes into play. Here we are dealing not with refraction, but with *reflection*.

When a beam of light strikes a reflecting surface its behavior is very much like that of a bullet striking a piece of impenetrable armor-plate. If it falls upon the surface perpendicularly, it will be reflected straight back toward the source. If it comes at an angle to the surface, it will be deflected at an angle exactly equal to that at which it struck.

Tho this action is like that of a bullet, we need not depart from our wave analogy to explain it equally well, for if ripples are stirred up in a shallow pan, they will be reflected from surfaces in just the same way as are the waves of light. They will demonstrate clearly the fundamental law of reflection: *that the angle of reflection of the beam is always equal to the angle of incidence* (Fig. 34).

Now the large parabolic mirror of a reflecting telescope may be considered as a figure made up of a great number of tiny plane surfaces, from which beams of light are reflected according to the angular law. Assuming that the beams of light are approaching the mirror

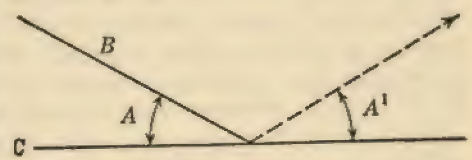


FIG. 34

The Law of Reflection. When the beam of light B strikes the reflecting surface C, the angle of reflection A¹ is always equal to the angle of incidence, A.

from a distant source, and therefore are parallel, the mirror will bring them to a focus because each point of its surface is so placed as to reflect toward a common center all rays striking it.

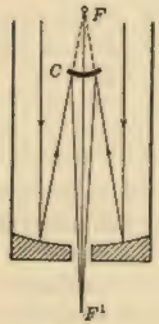


FIG. 35
How the Cassegrain Mirror Increases the Focal Length. The focus of the large mirror is at F, but the convex Cassegrain mirror C gives the beam a new focus at F^1.

The interesting thing is that, tho the process which has brought the light rays together in the focus of the mirror is different from that in the focus of a lens, nevertheless the same kind of image will appear. Moreover, identical principles with regard to the size of the image and the amount of illumination available for it will hold true. As in the refracting telescope, the magnitude of the image of a reflecting telescope depends on the main focal length.

In the Newtonian form, the second mirror performs no optical service. It merely reflects the converging beams of the large speculum to a point outside of the telescope, where the image may be examined conveniently with a magnifying eyepiece. But in the Cassegrainian reflector the small mirror serves to increase the focal length, and therefore to enlarge the image.

A comparison of Fig. 14 (page 58) and Fig. 35 shows why this is so. In the Newtonian type (Fig. 14) the focal point of the large mirror is not pushed farther away; it is merely bent at a right angle by the small mirror to bring it within reach of the eye. But in the Cassegrainian type (Fig. 35) the small convex mirror, placed inside the main focus, imposes a reflection from a second curved surface upon the converging rays, reducing their rate of convergence. In this way the Cassegrain telescope makes possible a much greater focal length without increasing the length of the telescope. The light actually traverses part of the telescope tube three times before emerging into the eyepiece, permitting a focal length two to three times the length of the tube without adding to the expense of construction or mounting.

Chapter X

THE ANCIENT ART OF GLASSMAKING AND THE MODERN ART OF MAKING TELESCOPES

I

SOMEWHERE in ancient Syria, perhaps as long ago as 4000 B. C., an accidental mixture of very hot sand and soda produced a liquid mass which, upon cooling, excited the awe and admiration of those who first beheld the miracle of glass.

How much we owe today to that unrecorded discovery a simple survey of any of our houses will reveal. To an astonishing extent we depend upon glass for useful utensils, for decorative pieces, for airtight portals through which daylight may enter, for lamp bulbs and chimneys, for electrical insulation, for aids to faulty eyesight, for mirrors; for a thousand and one uses which are steadily being added to until in the not-too-distant future we shall see buildings made of glass, furniture of glass, and no one knows what other things.

Despite its modern aspects, glassmaking is really one of the oldest of the arts. Knowledge of the making of glass passed rapidly from one country to another in the ancient world. Glass objects were common in Egypt. The Greeks placed great store by glass utensils and decorative objects. The Romans, not knowing how to make porcelain, used glass proportionately even more than we do today.

The glass industry, as we know it, really began with the invention of blown glass, in the first years of the Christian era.

Glass blowing consists of working the molten material with the aid of a blowing iron or pipe, an iron tube about five feet long, usually terminating in a knob upon which a daub

of hot glass can be affixed. The operator blows into the tube and the glass becomes a bubble, the thickness of its walls depending upon the amount of glass and the size of the bubble.

By swinging it, by putting it on the "marver"—a flat slab of marble—or by manipulating it with a variety of tools, the bubble can then be made to assume almost any shape. Hollow vessels, tubes, flasks, bulbs, vases and such items are made at will.

For the most part the methods used today in manipulation of glass are substantially the same as those developed during the Middle Ages and earlier. Only where machinery has speeded up the production and improved the uniformity of such products as bottles, electric-light bulbs and similar common articles has there been improvement in manufacturing procedures. The real advances of modern times have been in the betterment of chemical and physical control of the materials which go into the making, melting, heat treatment and cooling of the glass. These improvements, carried as far as science and art can take them, have made possible the branch of glassmaking of greatest interest to us: that which produces optical glass.

In the modern sense, *optical glass* is a very special sort, finer even than that used in making spectacle lenses. It is used only for optical instruments, such as microscopes, telescopes, spectroscopes and the like, the unique requirements of which demand a material of the finest quality, homogeneous, free from internal strain, innocent of bubbles, and as clear and transparent as possible.

II

Glass is a complex mixture of silica and an alkali (usually either sodium or potassium) together with a great variety of other metals and substances, each of which imparts to the finished glass some special quality. Unlike metals and most other solids, it is not crystalline in structure, but is what physicists call a "solid solution." The molecular arrangement of cooled glass is practically identical with that of liquid glass. There is no alteration of structure with cooling; no strict

regimentation of the molecules such as is found in crystalline solids. This quality is what gives glass its particular beauty and utility. Lack of crystalline structure is common to all true glass, but different kinds vary considerably in other respects, especially in transparency, color and homogeneity. Moreover, in such other fundamental characteristics (for optics) as diffraction and dispersion, different glasses that look alike may have wide variation.

Such characteristics depend on the ingredients of the glass, and also to an important extent upon the treatment of the material during manufacture. In old times the peculiar procedures of glassmaking were arrived at more by guess than by science. From Egypt to the Middle Ages each maker had his own methods and combinations, and, like rule-of-thumb cooks, some were good and some bad. It was fortunate that appearance and workability were the major considerations in those times, else such empirical methods often would not have been good enough to produce even such glass as was needed.

The invention of spectacles probably was responsible for the first attempts to improve glass with respect to its optical qualities. Most historians place the time of this discovery as about the last quarter of the thirteenth century, and the place as Italy, probably Florence. By the end of the fourteenth century spectacle-making had become an important industry in the Netherlands as well as in Italy, and trade in glass suitable for spectacles was brisk enough to figure in international commerce.

This glass was of the type now known as *crown,* a hard but workable material of which the chief constituents are silica of good purity, potassium or sodium, and other less important substances, usually the oxides of calcium and magnesium.

Flint glass, a soft, brilliant type used for cut-glass and later in combination with crown glass to form achromatic lenses, was first produced in England about 1675. It differs from crown glass mainly in that it contains a high proportion of lead oxide and less soda and potash. It is a heavy glass, brittle,

difficult to work, but of high refracting power, hence its great beauty in cut-glass ware.

Crown glass has a low index of refraction, and a relatively minor tendency to separate the colors of white light. Flint, on the other hand, has a high index of refraction and strong dispersion.

III

The manufacture of optical glass is a careful and scientific procedure. It goes without saying that the purest of raw materials must be used.

Into the charge in the melting furnace may go only the cleanest of fine white sand, source of the silica. This sand must be substantially free from traces of iron, which give glass a greenish tinge like that often seen in cheap bottles.

The alkalis which form the "flux" must also be of the finest quality. Whereas ordinary glass is often made with crude sodium sulfate or "salt-cake," optical glass may be made only with refined salts, usually sodium and potassium carbonate. Other needed ingredients, which include barium, calcium and magnesium, are put into the mixture in the form of carbonates. When lead is added, in the manufacture of flint glass, it is usually pure lead oxide.

These materials must first be ground as fine as possible by machinery, then thoroughly mixed. Thus compounded, the charge is ready for melting. In the case of most of the better optical glasses, this is done in a pot or crucible which is placed inside the melting furnace. Each pot holds several hundred pounds.

Preparation for the melting begins long before the glass is charged into the pot. The receptacle itself must first be brought up to near the melting point of glass. Sometimes this takes hours or days of steady heating in the furnace, for it is quite necessary to make certain that the pot will not crack or spall during the melting, also that traces of impurities in the material from which it is made, especially iron, will be burned out before the glass comes in contact with it.

Into the pot then goes the precious charge, a little at a time, carefully watched. The melting of glass does not result simply from the application of heat to the materials until they assume liquid form. It involves a chemical reaction, or rather a series of them. In the heat of the crucible alkalis are attacked by silica, which at high temperatures acts as a strong acid. There is a great deal of foam and boiling; time must be given after each addition to the charge for bubbles to form and pass off.

Several hours at the minimum are thus consumed in adding gradually to the molten mass, until all at length is reduced to semi-liquid form. At this point the glass is a sirupy mass, white-hot, sometimes filled with bubbles and heaving slowly with the rise of gases to the surface. The liquid is not a single, homogeneous material, but a mixture of many different compounds, mostly salts of silica, mingled with substances of much more complex chemical character, produced by the interreactions of the various materials in the charge.

Some may be volatile; hence their quantity will decrease if the glass is heated to too high a temperature, or held in molten form too long. Others have higher melting points than the average of the mass, and will solidify first if the temperature is reduced too slowly or the heat of the melt permitted to fall. Some, indeed, will have quite low melting points; remaining liquid after the rest of the mass has begun to solidify, they will gather in pockets, destroying the homogeneity of the glass.

Partly to prevent any of these unwanted things from happening; also to hasten the elimination of bubbles from the melt, the mouth of the pot is opened as soon as the melting is complete, and a stirrer inserted. It is a cylinder of ceramic material fastened to the end of a long iron bar. With a thrust like that of a spoon into molasses the workmen insert this implement into the resisting glass and begin a steady rotary stirring motion. Presently the heat of the furnace is shut off, but the stirring continues. The glass begins to cool; the stirring goes harder and harder. Now several men assist with the push-

ing and pulling of the bar through the stubborn, leathery material. Finally it is given up; the glass has got too hard to stir, and must be trusted to take care of itself from that point forward.

The pot is again sealed up and the slow process of cooling is allowed to proceed at a controlled rate which has been calculated from the known behavior of glass. It goes on sometimes for several days or weeks. When at length the pot is sufficiently cold to permit handling, it is removed from the furnace and broken open. Not until then does the glassmaker know whether he has been rewarded for his expense and pains. Because glass is a poor conductor of heat, the outer layer cools more rapidly than the inner ones, setting up stresses and compressions in the material which grow until the bursting point is reached. The glass then shatters along its lines of least resistance. When the pot is opened there may be nothing inside but a splintered mass of broken glass, or a bubbly, striæ-marked or discolored lump. On the other hand there may come out several quite large and quite good pieces; occasionally the entire content of the pot is found to be in a single sparkling chunk, good clear through and suitable for the making of a real giant of a lens.

IV

Most commonly the glass is found to have been broken into a number of irregularly shaped pieces.

The next step is to determine whether any flaws, such as bubbles or striæ, have impaired the usefulness of the surviving chunks. There is a simple way to test for such flaws. Each piece, placed in a glass tank, is immersed in a liquid which, by dissolving substances in it, can be brought to the same refractive power as the glass. At that point the edges of the glass seem to disappear; it is possible to see directly through the chunk as if it were not there. Flaws of any kind are revealed and can be located exactly. When they are near the edge of the piece they can sometimes be chipped or cut away, saving the rest.

Only a fraction of all the glass contained in the crucible may pass this test. The pieces that do are then ready for the next treatment: forming and annealing. The chunks are gently heated until the material becomes slightly plastic, but not molten. Each is then pressed or molded into a square plate or circular disc, of the requisite thickness for a lens and as large as possible. Sometimes the smaller discs are given a rough lens shape in the press, to diminish the work required to finish them. The larger pieces usually are pressed flat, and are commonly about 10 per cent greater in diameter than the finished lens to be made from them, and ⅛ to 1/10 as thick as they are broad.

These nearly-finished glass blanks are still not ready for the lens-maker. They must be annealed. This is a form of heat treatment intended to relieve internal strains. It is usually done in ovens equipped with thermostatic control, where the glass is held at high temperatures long enough for all stresses to adjust themselves.

When the finished pieces finally come from the annealing oven they must pass one more test—that to determine their optical constants, which include the indices of refraction and dispersion.

V

Casting large glass discs for telescope *mirrors* is a somewhat different matter. Here the transparency of the glass and freedom from striæ and minor flaws are not particularly important. The indices of refraction and dispersion are of no moment whatever. The glass is not really the mirror—it is simply the support for a reflecting coat of silver or aluminum.

The chief problem is the great size to which telescope mirrors have been pushed in recent years. Their magnitude alone introduces difficulties which increase about as the cube of the diameter. Were it to be made of iron or lead or even concrete, the casting of a flawless disc 100 or 200 inches in diameter would be something of a problem. How much more

so when it must be made of glass, and so freed of internal stresses that it will not warp, crack or lose figure!

Expansion and contraction come into the picture almost at once, and play an important rôle in the casting operation itself. It is therefore desirable to select a material for the disc that has the lowest possible coefficient of expansion. Telescope-makers ever since the middle of the last century have longed for the discovery of some ideal material, hard as quartz, workable as glass, easy to cast as concrete, light as aluminum, and above all, with no yielding one way or the other to changes of temperature.

Lacking it, they must seek the next best thing within reason. Fused quartz comes very near to being that substance. It has a very low expansion index; it works satisfactorily tho it is extremely hard; it takes a beautiful finish. But it is heavy, and moreover, it cannot be melted except in the electric furnace. Thousands of dollars and countless hours of time have been spent by professional and amateur mirror-makers in an effort to find a way to use this material. The most ambitious attempt was that undertaken by the late Dr. Elihu Thomson in his famous laboratory at Lynn, Mass., to devise a method for making the 200-inch mirror. The experiments only proved, unfortunately, that the cost of quartz at present is too great for large mirrors. Recently some smaller ones have been made successfully with it, including the Newtonian mirror of the new 36-inch reflector of the Royal Observatory at Greenwich.

It would be impossible to enumerate the various kinds of materials that have been tried for mirrors. Practically every experimenter has at last returned to glass, which has many advantages that more than make up for its deficiencies.

Ordinary commercial polished plate glass is used by telescope-makers with excellent results in mirrors up to 12 inches in diameter. In larger sizes the material must be selected with considerable care, but plate glass can be made to do for specula of quite respectable diameter. The 100-inch mirror of the Hooker telescope is made of a type of plate glass. So also are

the mirrors of the 72-inch Dominion Astrophysical Observatory and the 60-inch Ritchey reflector at Mt. Wilson.

Optical glass was the material of several successful mirrors made in America after World War I. They were manufactured by the Spencer Lens Company at Hamburg, N. Y., under the direction of Donald E. Sharp, glass technologist, and his associate, Walter Rising. By heating chunks of optical glass until they softened and filled the mold, Sharp and Rising turned out some very good 12-inch discs, then essayed larger ones. The first was a 23-inch for the Cincinnati Observatory. The largest, cast in 1921, was a 40-inch disc for the Steward Observatory 36-inch reflector.

A few years later, however, research produced an even better glass for telescope use. This was a low-expansion material developed by the Corning Glass Company, of Corning, N. Y., and widely known under the trade name of Pyrex. It belongs to the general group of glasses used for baking dishes, heat-proof laboratory ware, and recently even for teakettles and frying pans, and has a reaction to temperature changes only about one-fourth that of ordinary plate glass. Virtually all recent large mirrors have been made of it, including those for the sun-telescopes at Mt. Wilson Observatory, the 82-inch cast for the mirror of the McDonald Observatory telescope, the 74-inch at David Dunlap Observatory, the 120-inch optical flat cast for the California Institute of Technology, and the 200-inch discs cast for the Mt. Palomar telescope. With its development, America has become the acknowledged leader in making large telescope discs.

VI

Making telescope discs in this country is, however, already an old art. It began in the early nineties, when the optician George McBeth made some good ones up to 23 inches across. About 1895 a 60-inch disc was cast by the Standard Plate Glass Company of Butler, Pa., for the Rev. John R. Peate, who figured it into a mirror now reposing at the Smithsonian Institution.

Until World War I, however, practically all large discs were cast at the St. Gobain Glass Works in France, destroyed by the German offensive in 1914. It was the custom there to heat the glass in a huge crucible, which was then dumped quickly into a heated mold, a trifle larger than the intended mirror.

There is a limit, naturally, to the amount of glass that can be melted and handled in a single pot. The St. Gobain engineers managed it for the 60-inch Ritchey reflector, which was eight inches thick and weighed only a ton, but when the order came for the 100-inch mirror they were all but stumped. This disc would require nearly five tons of glass, considerably more than could be handled in a single pot. The problem was met by melting the glass in three pots, and dumping them into the mold in quick succession. It was not altogether successful, however; it resulted in a disc filled with layers of bubbles.

When the Bureau of Standards was asked, in 1928, to pour the 69-inch Perkins Observatory disc, the final melt was prepared in a furnace some distance off the floor, and the mold was countersunk into the ground. The glass was allowed to make its own way by gravity from the melting tank to the mold. A nearly perfect disc resulted.

A different and somewhat more picturesque method of handling the glass is employed by the Corning Glass Company. In making the two 200-inch discs the glass was handled in 400-pound ladles suspended from overhead trolleys (Plate 30). About 100 ladles were needed to fill the mold, considerable quantities of the glass being lost through cooling in transit. The chief advantage of this method, in dealing with very large discs, is that it permits the molten glass to be poured evenly over the surface of the mold, three equidistant doors giving access to the 20-foot circular "beehive" furnace.

Annealing large discs, needless to say, is a very important and delicate matter. The glass is allowed to cool rather quickly until the semi-plastic annealing temperature is reached. Here it is held for several days or weeks; then the heat is allowed to go off gradually, a degree or two a day, until the disc is cool. Cooling the 200-inch discs required about eleven months each.

VII

Whether for mirrors or lenses, the blanks of glass produced by so much effort are of course still only raw material. The telescope-maker's art is finally required to give them life.

It is an art at which comparatively few have excelled; one that requires a rare combination of skill, patience, resolution, experience and luck. Even the great Herschel found it necessary to figure 200 mirrors before he made a good one. Yet in many respects a good mirror is considerably easier to fashion than a good achromatic object glass, if for no other reason than that in a mirror only one surface needs to be worked, whereas in the simplest achromatic objective there are at least four. To which it may be added that the curvatures either of the mirror or lens must be true to within three or four millionths of an inch. An error so small that it may be detected only by the finest optical methods may be great enough to destroy the usefulness of the lens or mirror containing it.

The very difficulty of the task, and the fact that its problems can nevertheless be solved by anyone possessing the necessary amount of patience and perseverance, has attracted many to telescope-making as a hobby. Often these "amateurs" have led the professional telescope-makers in the excellence of their output. Herschel himself was an amateur when he started. Lord Rosse, Dr. Ainslee Common, the Americans Henry Draper and Lewis Rutherfurd, who did so much to advance the art of telescopic photography with instruments of their own making, were amateurs. Today thousands of men and women in the United States are engaged in making telescopes as a hobby, and some of these homemade telescopes are fine enough to inspire the envy of professionals.

For amateur or professional, the methods used in making mirrors or lenses are substantially the same. In the case of reflectors, the concave curvature of the mirror is first produced in spherical form, and gradually worked away into the paraboloid (Fig. 36). The initial step is to obtain a suitable glass for the speculum, and another, of equal size, to serve as a tool

for the grinding. Both must be circular discs of the same diameter.

The usual custom is to fasten the second piece to a firm post or to the top of a weighted barrel or small table in such a way that the operator has access to it from any direction. To the back side of the disc destined to become the mirror a handle is cemented; a smooth rounded knob of wood of a shape easily grasped does very well. First with coarse and later with finer abrasive, the upper glass is hollowed out by rubbing it across the lower. The rubbing, to produce this desired effect, must be of a special sort. Each stroke is made straight across the lower disc, and at intervals the upper disc is turned a little. Wear on the lower disc is meantime kept even by the bodily movement of the operator, who walks slowly and steadily around the post or barrel.

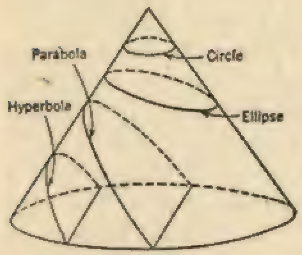


FIG. 36

The Relationship of the Various Geometrical Figures that Enter into Telescope-making. All are theoretically obtained by sectioning a cone.

Under the steady, slow strokes, the outer edges of the lower glass gradually are worn down, the surface becomes convex. At the same time the lower surface of the upper glass becomes concave. Presently a truly spherical figure is attained by both, for the simple reason that such surfaces are the only kind that can remain in contact during a rotational movement such as that given the two pieces by the operator. The longer the grinding is continued, the deeper the curvature becomes. Usually the rough-grinding of the spherical surface is finished in 1 to 2 hours for small specula. Larger ones take longer.

One abrasive used for this part of the work today is carborundum, a carbide of silicon. Prior to its invention in 1898 telescope-makers used emery, which cuts only about a sixth as fast as carborundum. With the latter material a six-inch mirror

can be rough-ground to curve in less than an hour, but with emery it would require six hours; for larger mirrors very considerably longer. It was with emery that William Herschel put in the famous sixteen-hour vigils over metallic specula, while Caroline placed food in his mouth and cheered him with stories.

The movements necessary to produce the spherical curvature are slow, methodical and mechanical. Hence a machine of proper design can do the job as well as a man, and for large

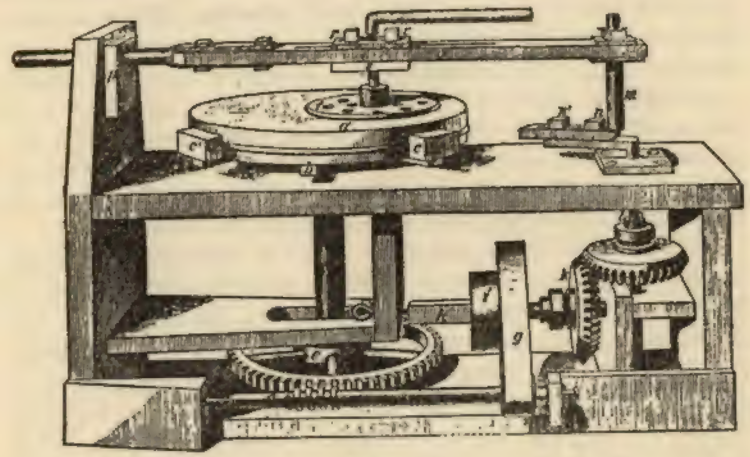


FIG. 37

Dr. Draper's Grinding Machine.

discs such a machine is not only desirable but necessary. Several kinds have been designed, all patterned more or less after the grinding machine described by Lord Rosse. Dr. Henry Draper made one of the first contrivances of the sort in this country (Fig. 37) and used it successfully to grind large mirrors for his photographic telescopes. The making of such mirrors as the 100-inch and 200-inch would be utterly impossible without a grinding machine. Plate 17 shows the 100-inch mirror on its machine.

VIII

The rough-grinding is neither the most difficult nor the most tedious of the processes through which mirrors must pass before they are ready for gazing at the stars.

When the curvature has been brought near to the proper focus, the fine-grinding begins. This may be done in the same way as the rough-grinding, except with finer grades of carborundum. When, by frequent testing, the telescope-maker concludes that he has reached a good spherical surface, with a focus of about the proper length and a surface free from scratches and pits, he washes his embryo mirror free of all carborundum, changes his clothing, and if convenient even moves his apparatus into another room, and proceeds with the process of polishing. Extreme care must be used to prevent so much as a single speck of abrasive reaching the glass now, or it will result in an ugly and sometimes ruinous scratch.

At this stage the convex glass "tool" is replaced by a "lap" of optician's pitch, and the polishing is done with the aid of jeweler's rouge instead of carborundum. The object of the polishing is to cut down the rough surface left by the grinding, and to reduce the fine gray surface of the ground glass to a smooth, brilliant, mirror-like surface ready for the figuring. The polishing takes about six hours for a small mirror. When it is finished a bright, smooth surface appears in the concave face of the mirror.

Then comes the almost incredibly delicate task of "figuring." This consists of working the figure from a spherical surface to that of a paraboloid. The difference in curvature is not great; often it is too small to detect by any ordinary means; yet the difference is of paramount importance in the performance of the telescope. A spherical surface cannot give a sharp image free from spherical aberration; the paraboloid does.

Telescope-makers use various methods for this delicate task. The older experts, including Herschel and Lord Rosse, preferred to do it by the skilful manipulation of the pitch lap, lengthening or shortening the stroke as needed. Modern mirror-

makers find that it can also be done by altering the face of the lap slightly, or by using a smaller tool. No matter what method is used, the success of this part of the work calls for all the patience possessed by the maker, and it is here that the performance of the finished mirror is determined.

The curve produced by the earlier grinding and polishing is parabolized by deepening it slightly at the center. It is fortunate that a simple optical test, originated by Foucault, provides the mirror-maker with a means of determining the trueness of his curve with exquisite accuracy. The test also shows him the location of bumps, hollows or irregular places. The elimination of these is another matter, and each fault must be treated individually, sometimes with special motions with the figuring tool, or with small special tools contrived to correct the fault without materially affecting the rest of the mirror.

The Foucault test consists of illuminating the mirror with light from a small pinhole, or "artificial star," placed just a trifle to the side of the axis. The eye is applied to a point an equal distance on the other side, where the rays should converge. If the mirror is perfectly spherical, the disc will be equally illuminated with light. Now, if the eye is moved back a little, and a sharp blade, held vertically, is moved into the focus from one side, the entire disc will be seen to darken uniformly. If the blade is brought across the beam of light inside the focus, the disc will be darkened as if by a shadow approaching from the same direction as the blade; if outside the focus the shadow will appear to be approaching from the opposite side.

If the mirror surface is not perfectly spherical, its deficiencies of figure will be revealed by the distribution of shadow over its face, since the light from various parts will not be focused at one point. The shadows appearing on one side of the disc, for example, will be due to light focused past the main focus, those on the other to light focused short of it. The test, so simple that it can be set up in any small workshop, is actually

more accurate than necessary, for mirrors with obvious defects as tested by it will serve well in astronomical work.

The mirror may be finished either by silvering or aluminum-coating its concave surface. The silver process is similar to that for commercial silverplating of ordinary mirrors, except that the reflecting surface is placed on the front of the mirror. No light passes through the glass except that which the silver film is unable to reflect.

The silver is at its brightest when first deposited. It begins to tarnish at once, but with proper care it will maintain a high reflecting power for several months; in some climates for more than a year. Usually, however, it is necessary to dissolve off the tarnished coat and put on a new one every six months or so. Aluminum (see page 172) has several advantages over silver, particularly in its resistance to tarnish.

IX

The making of achromatic objectives for refracting telescopes is in one sense simpler than that of making a mirror for a reflector, since the curvatures do not need to be other than spherical. However, there are more curves to be considered, and these complicate the matter enormously. Even the simplest double convex lens, which is, of course, not achromatic, has two spherical surfaces. These must be not only approximately perfect in curvature, but also exactly centered on each other.

In achromatic objectives, two lenses are to be considered, the crown and the flint. Given the optical constants of the pieces of glass with which he is dealing, the lens-maker can determine with the aid of algebra the curvatures and other characteristics his combination will require to be substantially achromatic. Data worked out on a scientific basis by investigators in this field will then help him to decide what combination of curvatures will be necessary in his achromatic lens to insure it against that bugbear of the old-time telescope-makers, spherical aberration.

A frequent combination is a double convex lens of crown

glass, and a flint lens with one side concave to fit the inner side of the convex crown, the other side plane. The radii of the surfaces of the convex lens in this case will vary as 2 to 3, usually with the deeper curve on the side toward the flint, which will then have an accordingly deep concavity. Another frequent combination is a crown lens of convex curvature equal on both sides, coupled with a flint lens concave on one side, to fit the crown, and plane on the other.

In grinding such lenses, the convex crown may be made to serve as the rough-grinding "tool" upon which the concave surface of the flint is ground. This produces two of the curves at once, and moreover, insures a perfect fit. The others are rough-ground with the aid of suitable tools. The fine-grinding and polishing is then done, as in the case of a mirror, on pitch laps with fine rouge. The final corrections of figure, often more difficult than in mirrors, must be made by various methods after the polishing has been completed.

It is unfortunate for the object-glass-maker that for correct surfaces there is no simple, accurate test like the Foucault test for concave surfaces. He must judge the figure of his crown lenses, in the last analysis, by the way they work, and corrections often must be made by old-fashioned trial and error.

Chapter XI

GOOD SEEING, MAGNIFICATION, DEFINITION, CATCHING THE INVISIBLE LIGHT

I

TO the astronomer the atmosphere is an ever-present adversary. It baffles, confuses and thwarts him. It permits him tantalizing moments in which the object of his research appears with amazing clarity; then maliciously it snatches the image away, distorts it, beclouds it, causes it to dance in the telescope with maddening gyrations.

Again, the air may be like a murky ocean filled with fine floating sediment. Dust storms are familiar to persons living in arid and semi-desert countries; they are familiar in a more subtle and exasperating way to astronomers, for very often the atmosphere carries enough dust, even in well-watered climates, to becloud the telescope. Fogs and rainstorms are also fatal to the use of the telescope.

Nor does even this catalog of woes complete the list. The air alone, unaided by moisture, dust or smoke, can be the most abominable of all. Often without apparent cause, it contrives to produce such aberrations in the image—such distortions, flickerings, dancings—as wholly to ruin the seeing. The reason is that air, like the surface of a pond, may be filled with ripples and wavelets. These act to cause slight changes in refraction. Seeing through them is about like trying to look through cheap window glass, with the added difficulty that the "striæ" of the atmosphere are in motion.

The nature and extent of the damage that such ripples will cause to the image in the telescope depend upon the relation between their wave-length and the aperture of the instrument.

Ripples wider than the aperture are of less consequence than wavelets only half or a third its breadth. Large waves will cause the image to move; but the motion is communicated to it as a whole, and not to the parts separately. On the other hand, short ripples act to change the focal length of portions of the objective with relation to others; thus they produce distortion.

Some causes of air ripples are known, and in the main they are produced by temperature variations. Very often the disturbance is near the ground and of local origin. The heat from chimneys or buildings, reflection from fields of stubble, temperature aberrations caused by the presence of a small pond or lake nearby, may cause disastrous ones.

Newton, in his *"Opticks,"* gave consideration to this problem, and suggested one solution that has been tried with fair success:

"If the theory of making telescopes could at length be fully brought into practise, yet there would be certain bounds beyond which telescopes could not perform. For the air through which we look upon the stars is in a perpetual tremor; as may be seen by the tremulous motion of shadows cast from high towers, and by the twinkling of the fix'd stars. The only remedy is a most serene and quiet air, such as may perhaps be found on the tops of the highest mountains above the grosser clouds."

Such ideal spots are indeed sought as locations for great observatories. When Lick Observatory was established atop Mt. Hamilton, in California, the success of this location was such as to give mountaintops a great vogue. Mountain locations have since been used in all parts of the world. Mt. Wilson Observatory, as the name suggests, is located at such a site. The new McDonald Observatory has been built on a peak in the Davis Mountains of Texas. The 200-inch telescope also views the heavens from an elevation: Mt. Palomar, 6,126 feet high, near San Diego, California.

But mountains have not proved uniformly successful. Some lie in country where local disturbances, including updrafts and high winds, destroy the seeing. Others are too high, and the

intense cold of their winters makes observation difficult or impossible. Many are inaccessible.

Fortunately good seeing is not found only in mountain locations, as countless tests and the experience of observatories have demonstrated. Many astronomers today hold that the most likely locations are high, semi-arid plateaus. The Lowell Observatory has such a situation at Flagstaff, Arizona; the Harvard Observatory's southern station near Bloemfontein, South Africa, occupies a similar site.

Again, good seeing may be found over widely distributed areas of the earth, and it often appears to bear no relation to latitude, altitude, climate or proximity of the ocean. The Pacific coast is usually considered good; in the same latitudes the Atlantic seaboard is frequently bad. The Dominion Astrophysical Observatory, where seeing is of the best, is located on a small hill near the city of Victoria, B. C., only a few hundred feet above the level of the Pacific. At its Oak Park Station, only twenty-five miles from Boston, the Harvard Observatory enjoys good seeing through a major portion of the year.

II

The question of magnification enters into every practical consideration of telescopes, and is of great importance. But the popular notion that the major function of a telescope is to magnify is a misconception. For reasons that will bear further examination, magnification is not the main consideration, perhaps not even a major one. Sometimes it is objectionable.

The amount that any telescope will magnify is easily calculated, and depends on the relation of the focal lengths of the lenses or mirrors. It is determined simply by dividing the focal length of the objective or speculum by the focal length of the eyepiece—a formula stated thus: F/f, where F is the length of the main focus and f the focal length of the eye-lens. Assuming a focal length of the eyepiece, for example, of two inches, and a focal length of the objective of 100 inches, the magnification will be F divided by f, or 50 diameters.

Logically it would seem, if the matter is as simple as this, that the magnifying power might be pushed up to almost any point. We might consider, for example, the construction of a telescope of 1,000-foot focal length, with an eyepiece of 1/1000th of an inch focus, producing an instrument capable of magnifying 12,000,000 times. This would surely bring the moon or planets close enough for the most careful scrutiny, and end once and for all any remaining questions or doubts about them! But practically such a telescope would be utterly useless.

In air, magnification not only enlarges the image, but it also increases the apparent movement in it, aggravating the aberrations produced by ripples. Even if this were not true, magnification cannot produce more detail than exists in the image, and may in fact lose some of it.

We have noticed how quickly mechanical difficulties appear when an attempt is made to build telescopes of very large aperture. With increasing aperture, too, the aberrations produced by the air become more pronounced, until in very large instruments it is sometimes necessary to quiet the image by *reducing* the aperture temporarily with a diaphragm.

If high magnification were used under such circumstances the movement of the image would be increased to such an extent as to make work impossible. At the best of seeing, magnification so intensifies the movement of the image as to cause it to appear, in a large telescope, to be swimming in a turbulent and all-but-visible liquid, or like an object in the bottom of a clear but swiftly-moving stream.

Most large telescopes are provided with eyepieces that make possible a magnification up to 4,000 or 5,000, but in practise 1,000 diameters is as much enlargement as can ever be used; with most work the magnification is 500 or thereabout.

III

There is another phase of the atmosphere's interference with astronomical investigation that we have not so far considered. It is the absorption of light by the cottony blankets of the air

that cover us. This effect is not the same as that of dust or moisture in the air; it represents the activity of the molecules themselves.

Atoms and molecules, as Kirchhoff showed in his famous explanation of the dark lines of the spectroscope, have power to take up the same wave-lengths as they themselves emit when stimulated to give off light. When rays from any celestial body pass through the atmosphere, they find in it a great aggregation of atoms, molecules, ions and other types of particles, each capable of responding to specific wave-lengths of light and thus absorbing part of them. A portion of nearly all waves, from the invisible heat waves up to the ultra-violet, is absorbed, the amount of absorption varying considerably for different parts of the spectrum. The absorption is not very pronounced in the visible spectrum, but it increases sharply in the ultra-violet range. At a certain point in the shorter part of the ultra-violet practically all is absorbed.

From a biological point of view this is most fortunate. Dr. C. G. Abbot has shown that life would be impossible if the full ultra-violet radiation of the sun were to strike the earth, because of the powerful chemical and other action of these invisible rays. We are thus indebted for our existence to a thin layer of molecular oxygen in the form called *ozone*. If all the ozone in the atmosphere were gathered together into one layer it would scarcely be half an inch thick, yet this material is so opaque to very short rays of ultra-violet light as to absorb them almost completely.

This is no boon, however, to the astronomer and the astrophysicist, to whom a study of all wave-lengths is important. The various kinds of light are tell-tales of what is going on, at least in the outer layers of the sun and stars. The amount of light of each wave-length emitted is a kind of index of physical reactions taking place.

Short of establishing his observatory outside the earth's atmosphere, which is at present impossible, the astrophysicist must seek a location where the layer of air above him is thin, and make sure that his telescope is catching and transmitting to the image all of the light, both visible and invisible, that actually filters through to it.

The first drives him to mountain-tops, providing a double reason for the excellence (where local conditions do not destroy the seeing) of such sites. Seeking higher elevations would be of no practical use, of course, if the atmosphere were a homogeneous uncompressible liquid of uniform density, like a body of water. But the air is a gas; its density increases rapidly with the depth of the layer. It is very much denser at sea level than at higher points, so much so that tho the total thickness of the atmosphere may be more than 100 miles, nine-tenths of it is contained in the first ten miles above sea-level.

A relatively low mountain will give access to air considerably less dense than at the seaboard; a high mountain pushes up into rarefied strata to such heights that, in the cases of giants like Mt. Everest, Kanchenjunga, and several others, it is impossible for men to breathe there fast enough to support life without an auxiliary oxygen supply.

It would be impractical to establish an observatory on such heights. Mountains between 6,000 and 8,000 feet high, in the temperate zones, are probably most satisfactory from a practical point of view. Mt. Wilson and Mt. Hamilton are examples of moderately high mountains suitable for observing under comfortable circumstances. Mt. Wilson has an altitude of 5,700, Mt. Hamilton of 4,200 feet. Many other mountain-tops in the Sierras and in South America and Africa are equally suitable, and some of them are already in use or under consideration as observatory sites.

IV

A study of the problem of catching the invisible light has shown that telescopes themselves can be improved as regards their capacity in this respect.

In the case of refracting instruments, some improvement can be obtained by arranging the telescope entirely for photographic use, and figuring objectives in such a way as to focus particularly the kind of light desired, whether ultra-violet,

visible or infra-red. By this means all the radiation of that kind caught by the objective (and discounting the unavoidable and often very serious losses in transit through the glass) can be brought to fall upon the photographic plate.

When it comes to catching the invisible light with the reflecting telescope, we find that the friendly coating of silver, which proved such a boon to telescope-makers tired of wrestling with speculum metal and its problems, is not such a good friend after all. For tho silver reflects a major portion of the visible light and some of the infra-red, it is almost completely transparent to the ultra-violet. This valuable part of the spectrum is allowed to pass almost unhindered. Since the light must be twice reflected—once by the large mirror and again by the small one—the ultra-violet which does happen to be reflected by the large speculum is likely to escape through the small one.

The problem of what to do about this has at last been solved in a most remarkable way by Dr. John D. Strong of the California Institute of Technology. The trick is to coat the mirror with a fine skin of bright aluminum instead of silver. Aluminum reflects ultra-violet radiation remarkably well. Near the upper limit of the wave-lengths transmitted through the atmosphere, 83 per cent of the ultra-violet falling on an aluminum mirror is reflected, whereas a silver mirror reflects only 8 per cent, or less than a tenth as much.

It is true that in the visible part of the spectrum a freshly-deposited coat of silver is a somewhat better reflector than aluminum, but this is soon offset by the tarnishing of the silver, which quickly causes a diminution of its reflective ability. A few days or weeks after the fresh silver coat has been applied it is no better as a reflector than an aluminum coat, which is quite permanent and does not tarnish.

The advantage of aluminum as a reflector of ultra-violet light has been known for some time, but no method for applying a thin layer of the metal evenly over the curve of the speculum had been found. Dr. Strong's contribution was a procedure for accomplishing this in a practical, simple manner.

The glass is prepared by thorough cleansing. The surface

must be scrubbed with chemicals and finally blasted clean with an electrical discharge from high-voltage terminals. When this part of the process has been completed, the mirror is placed in an airtight chamber and a high vacuum produced with an air pump. The aluminum is then evaporated from the surfaces of coils of tungsten wire which are heated by passing an electric current through them. The aluminum, previously coated on the surface of the wire, melts, then evaporates in the vacuum. As a vapor, it settles on the surface of the mirror like steam on a cold window.

The aluminum thus deposited produces its own protective covering in the form of a hard, transparent skin of aluminum oxide, which is chemically identical with the material used in the production of artificial sapphires. The aluminum oxide is strongly adherent to the glass, more so than silver. It is so tough that it can be cleaned simply by scrubbing with soap and water, treatment that would ruin a silver coat.

More recently an improvement over this process was announced by Robley C. Williams of the physics department of Cornell University, in a letter to the editor of the *Physical Review*. After careful cleaning, the mirror is coated with chromium by evaporation, and the chromium layer in turn is coated with aluminum by the Strong process.

This kind of laminated layer, Mr. Williams reported, has remarkable properties. Rubbing the film with a blunt steel instrument or even steel wool affects it only slightly. Rubbing it as hard as possible with cheesecloth reduces but little the reflecting power of the coat. Even when soot, dampened with kerosene and mixed with sand and grit, was placed on such a film and cleaned off with alcohol and water twenty successive times, only slight scratches were observed.

The discoveries of Dr. Strong and Mr. Williams stimulated a number of scientific workers to deal experimentally with the problem of permanent aluminum coatings. Several small telescope mirrors having been coated with aluminum successfully, in the spring of 1934 the 36-inch Crossley reflector of Lick

Observatory (Plate 24) received a coating of it by the Strong process—the largest mirror to be so treated until that time.

It is expected that the mirror of the 200-inch telescope will also be aluminum-coated. Since the work of this huge instrument is to be mainly photographic, such treatment will increase its effectiveness in the ultra-violet nearly ten times over that estimated when it was designed. Astronomers believe that in time practically all telescope mirrors will be aluminum-coated, especially those used for photography or spectrographic investigation.

Chapter XII

INSTRUMENTS THAT HELP TO MEASURE AND INTERPRET WHAT THE TELESCOPE SEES

I

WHEN Galileo turned his tiny 30-power telescope to the heavens in those first exciting sessions at Padua, he had only his eye and his judgment of distance, both uncertain, to aid him in measuring celestial angles. His little telescope magnified the discs of the planets, brought more stars into view, and enlarged the intervals between them, but it afforded him no means by which the exact extent of those magnified intervals or planet-discs could be determined.

Such a state of affairs, of course, could not long be tolerated. We have seen how some of the old-time astronomers met this problem, with "telescope sights" on their quadrants and sextants, and the introduction of cross-hairs and micrometer wires into the main focus of their Keplerian telescopes. In visual work today the *filar micrometer,* so called because it has fine threads across the field of view, is a practical necessity.

The general principle is shown diagrammatically in Fig. 38. It consists of a main frame *A,* upon which are two sliding frames, each separately controlled by a fine-thread screw. The sliding frame *B* carries a vertical spider-web line *S,* which serves as the "fixed thread" of the instrument, and one or more horizontal threads, *H.* The second frame *C* slides on *B,* and carries a second vertical spider-web line *V* and usually a comb or other device which registers adjustments amounting to whole turns of the micrometer screw *D.*

To use it, the astronomer adjusts the fixed thread *S* upon one star, with the aid of the screw *E.* He then turns the screw *D*

until the second vertical line V is exactly on the second object to be measured. The number of turns of D necessary for the adjustment can be read from the comb and the graduated head of the screw. These are reduced to angular distance by applying the known constant of the instrument, which of course must be determined by tests.

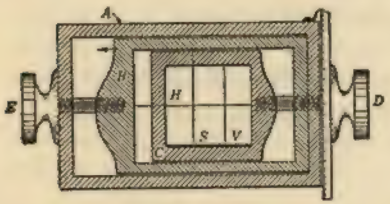


FIG. 38

Scheme of the Filar Micrometer. The main frame A carries two sliding frames B and C, each separately controlled by screws, E and D. B carries the "fixed thread" S, and one or more horizontal threads H. C carries the vertical thread V and a comb which registers the number of full turns of D needed to make an adjustment.

In more elaborate examples, a small electric light is supplied to illuminate the cross-lines against the field, or to spread a little diffuse light in the field against which the lines show up dark.

Other types of micrometers include the ring micrometer, in which the distance between two stars is calculated by the time it takes them to cross the parts of an opaque ring while the telescope remains fixed, and the square bar micrometer, which works on the same principle. These micrometers are now seldom used, chiefly because they require the application of considerable mathematics for the reduction of the distances, whereas the comparatively simple filar micrometer gives results that are at once accurate and easy to obtain.

For finding angular distances that are greater than practicable for the filar micrometer—distances, say, up to one degree of arc or more—recourse may be had to a type of micrometer attributed to Fraunhofer. This works on the principle that if a lens be split evenly along a diameter, and the halves slipped upon each other along the line of cleavage, the image of every object in the field will be double, since each half of the lens will form its own set of images.

It follows that two objects, such as stars, which are quite

widely separated in the united field, can be brought exactly together by proper manipulation of the half-lenses. Their angular distance may then be determined from the amount by which it has been necessary to slide the halves of the lens.

Any lens in the optical system of the telescope will serve, but in practise splitting the objective gives the best results. This is the principle of the *heliometer*. As we have seen, Fraunhofer made such an instrument for the observatory at Königsberg, and F. W. Bessel used it to obtain the first determination of the parallax of a star. Heliometers are rather rare, since the work they do can be accomplished with less effort by photography today; nevertheless, there are some large ones in use. An especially fine one, of six inches aperture, is included among the major instruments of Yale University Observatory.

II

The photographic plate made the micrometer obsolete in many kinds of astronomical work, but brought with it a new set of problems. The plate records the images of the stars at their proper places, but the angular distances of objects shown there do not measure themselves; there is still the matter of reduction.

Of great importance is the type of photographic work in which determinations are made of the amount which a celestial body has moved during a given time; observations which reveal the presence of asteroids or a planet, or the proper motions of stars. The magnitude of this motion can be learned with comparative ease if it is fairly rapid. The equatorially mounted telescope, equipped with an accurately adjusted driving clock, keeps the photographic plate in motion exactly with the images of the fixed stars, and they will be photographed as single brilliant points of light. If one body among them moves appreciably with relation to the others during the time of exposure, its photographic image will not be a sharp point, but a streak, a short line, or an oval blur, depending on the movement at right angles to the line of sight during the exposure.

The angular motion of meteors, of course, is readily obtain-

able in this way. So may be that of the relatively fast-moving asteroids if the time of exposure is very long. But when it comes to a distant planet, such as Pluto, and more particularly to the determination of stellar proper motions, no single exposure can be long enough to produce any appreciable line upon the plate.

In such a case successive exposures are made of the same part of the sky a year or several years apart, and the movement of any body in the interval becomes noticeable. Sometimes the difference is great enough to be revealed when the two plates are simply held together and looked through. A more certain method of detection is to be found in the *blink microscope.*

This is a double microscope so arranged that two plates to be compared are inserted at once. With the aid of a clockwork device, the plates are viewed alternately in rapid succession. If there has been any movement of a body pictured on the plates during the time interval between them, its image will seem to jump back and forth between the old position and the new, while all others will stand perfectly still.

With a blink microscope the young astronomer Clyde Tombaugh spotted the planet Pluto at Lowell Observatory, in the course of a series of investigations initiated by the late Prof. Percival Lowell and carried on by Dr. V. M. Slipher, director of the observatory. Such instruments are in daily use at many large observatories, and are among the most useful of the lesser auxiliaries of the photographic telescope.

If the blinking mechanism of the microscope is shut off, and both plates are viewed at once, motion in any body during the interval between the exposing of the plates can sometimes be detected directly from the stereoscopic effect, which makes the second image appear to stand out from the background of the other stars. This is the principle of the *stereoscopic comparator,* or stereo-comparator.

III

We now come to the problem of determining the magnitudes of the stars, and measuring the relative brightness of variable stars in their various phases. We have seen that classification of stars according to "magnitude" was begun by Hipparchus in his great star catalog. His magnitudes were arrived at, of course, by visual estimates. Such estimates, in which the stars are classified in the order of brightness as judged by the eye, continued in use until the nineteenth century, and the visual method was used even by the German astronomer F. W. A. Argelander as late as 1870 to determine the variations in brightness of the variable stars. Argelander's method was to compare the star under observation with others of known magnitude in the same neighborhood, including a star just a little brighter and one just a little less bright.

In this manner he found it possible to obtain the magnitudes with excellent accuracy, but the method suffered in the hands of others because of individual differences in judgment and eye accuracy. A complicating factor in judging brightness is introduced by the colors of stars. If two are actually of the same magnitude (as measured instrumentally by total light output) but one is red or yellow and the other blue, the blue star will appear bigger and brighter to the eye, hence will be classified as of greater magnitude.

When it became apparent that greater accuracy was needed, a study of the magnitudes so far assigned showed that the brightnesses represented by these conventional assignments could be almost exactly expressed by assuming that a difference of five magnitudes corresponds to a difference of 100-fold in brightness, and that each magnitude differs from the next in brightness by the fifth root of 100. This provides a very satisfactory method of dealing with the problem, for by the use of logarithms the actual difference in brightness between any two stars is readily computed from their magnitudes.

Nevertheless, it does not solve the main problem—that of finding out with scientific accuracy what these differences are. Several types of *photometers* have been used to aid the eye in this determination. One kind interposes a sliding wedge of glass across the image of the star, and the magnitude is determined by measuring the point at which the image disappears.

Another method provides a comparison of the actual star with an "artificial star," a pinpoint of bright light corresponding to a known magnitude.

A more elaborate photometric method makes use of polarized light. When light comes to us from a star, each beam contains rays the waves of which are vibrating in various planes with respect to the axis of the beam. This may be visualized by considering each train of light waves as waves in a rope held between two fixed points. If the cord is struck, transverse waves run along it, all in the same plane. Consider now a beam of light consisting of many such cords, vibrating in all possible planes, and you have a mechanical picture of a beam of non-polarized light as it comes to us from the sun or stars.

Certain kinds of crystals, notably those of Iceland spar, have the curious property of transmitting light rays vibrating in one plane, and absorbing or deflecting those vibrating in all others. Thus, if an ordinary beam of light is passed through a crystal of Iceland spar, two beams will emerge, at different points. One of these will consist of polarized light, or light in which all the transverse waves are vibrating in the same plane; the other will be ordinary light.

The explanation of how this phenomenon can be employed to measure the brightness of a star is somewhat complicated. It involves the use of one or more Nicol prisms, which are made from Iceland spar by cutting the crystals in a certain manner and cementing the pieces together again with Canada balsam. The result is a cell which transmits only polarized light and absorbs the ordinary light.

If two such Nicol prisms are used, the polarized beam emitted by one will pass through the other undiminished, provided the crystal axis of both is the same. But if one be rotated, more and more of the polarized beam will be absorbed until, when the rotation has progressed through 90 degrees, all of the beam will be taken up in the second crystal. Under certain circumstances the same effect can be obtained with a single Nicol prism and a plane mirror.

To use this effect in a photometer the brightness of a star is compared with that of another of known magnitude. The light of one is passed through the Nicol prisms, and the second prism is rotated until both stars appear of equal brightness. The actual difference may then be calculated from the amount by which it was necessary to turn the second prism. The late Professor E. C. Pickering and his associates did most of their remarkable work on stellar magnitudes at Harvard Observatory for the great Harvard catalog with such a contrivance, but the method is now little used; magnitudes today are obtained photographically.

But, as usual, new problems are introduced. In the first place, stars do not appear of the same magnitude to the eye and to the camera. The eye is most sensitive to the green and yellow rays, while the photographic plate is especially sensitive to the blue and ultra-violet. Eye measures of stellar magnitudes are therefore measurements of brightness in the green and yellow; photographic measurements are expressions of brightness in the blue and ultra-violet.

By making use of a light filter on a telescope designed for visual use, and special photographic plates sensitized to the green and yellow, astronomers are able to determine stellar magnitudes by photography, however, that correspond closely to magnitudes found directly by the eye. The filter absorbs the blue and ultra-violet light (which in visual telescopes is not focused as sharply as the other rays, and hence would produce a blurred image on the negative), and permits the taking of images as sharp as those that would be obtained in regular photographic telescopes.

From such plates the magnitudes of the stars can be determined directly by measuring the diameter of the star images, for the size of the image is not a measure of the actual diameter of the star, but rather of its brightness. Another method is to change the time of exposure of the plate according to a definite ratio. In very short exposures only the brightest stars will be pictured. As the length of exposure is increased, successively fainter stars appear on the negative. The time of exposure

needed to show the stars in a given field will therefore serve as an index of brightness of at least the faintest of them.

A third photographic method consists of taking a photograph of the field with full exposure, and then another with the aperture of the telescope reduced by a given amount, say by partial closing of the opening by a diaphragm. Since diminution of the aperture reduces the amount of light received by the telescope, a comparison of two plates taken in this way indicates the differences in brightness.

Within recent years a great deal of work has been done to provide direct reading of stellar magnitudes by electrical means, particularly with the aid of the photoelectric cell. One of the most thorough programs of research to adapt this ultra-modern invention for astronomical work was carried on prior to 1930 at the Research Laboratory of the General Electric Company by Dr. G. F. Metcalf and B. J. Thomson. It resulted in the development of a vacuum tube for amplification of the feeble currents generated in photoelectric cells by stellar radiation. In effect the device was a radio set attached to the eyepiece of a telescope, amplifying the feeble light signals of the stars as a radio amplifies the distant sound signals from a broadcasting station.

Carrying on this work at Washburn Observatory of the University of Wisconsin, and later at Mt. Wilson Observatory with the 100-inch telescope, Dr. Albert E. Whitford and Dr. Joel Stebbins, director of Washburn Observatory, were able to report to the National Academy of Sciences in the spring of 1934 that they had developed a photoelectric cell-vacuum tube amplifier system of most astonishing sensitivity. The device, the *thermionic amplifier* (Plate 21), is capable of detecting without telescopic aid the light of an ordinary candle thirty miles away. Used in conjunction with the 100-inch telescope it can detect a light no brighter than a candle at 3,000 miles. It can measure the faint luminosity of the sky far beyond the range of the most sensitive photographic plate, and it determines stellar magnitudes more precisely than human eyes or photography can ever hope to do.

It is still too early to say what ultimately can be accomplished with the thermionic amplifier. As an example, Drs. Stebbins and Whitford reported that they had been able to measure the amount of dust that lies in space among the stars by the reddening effect it produces in light passing through. The position of the solar system in our galaxy has been more exactly determined with this instrument. The galaxy itself was shown not to be quite as large as formerly thought.

Turning their amplifier upon extragalactic nebulæ, Drs. Stebbins and Whitford have discovered that the Great Nebula in Andromeda, formerly thought to be considerably smaller than our own galaxy, in reality is very likely nearly as large. Beyond the edges of this nebula, far into regions where the photographic plate detects no sign of luminous material, the thermionic amplifier reveals the presence of hundreds of thousands of luminous stars. The extension of the Andromeda nebula, the astronomers surmise, is typical of what may be found for other such objects, the smallness of which, as calculated by older methods, may be due merely to the insensitivity of the photographic plate.

IV

We come now to a consideration of the invention of Fraunhofer and Kirchhoff: the spectroscope, and its photographic companion, the spectrograph. To these instruments may be attributed the modern science of astrophysics. They have brought the stars, the sun, the comets and the nebulæ into the physical laboratory for examination, provided a classification of stars according to chemical composition, temperature and other factors, and hence according to their ages. The spectroscope has made it possible to determine the speed and direction of stellar movements *in the line of sight;* hence it supplements the evidence of the camera in providing a complete three-dimensional picture of stellar movements. It also reveals the existence of many double stars so close together that their distinct images are not resolvable even in the largest telescopes, and tells the comparative size of the members of the double, the direction of their rotation,

and their relative velocities and masses. Finally, the spectroscope has been the progenitor of a variety of new instruments.

The essential parts of this contrivance are: a narrow slit through which the light enters, a "collimating lens" to gather the light together, one or more wedge-shaped prisms of optical glass upon which the light falls, and a second lens and eyepiece through which the resulting band of color with its dark or bright lines may be examined (Fig. 39). Many kinds of spectroscopes have been designed for different purposes, but this essential structure is the same in all. The only major variation is when a "diffraction grating" is used in place of a prism. The grating is a sheet of glass or metal ruled with very fine even lines, which produces the same kind of color dispersion as a prism. It has certain advantages, including the fact that it will form a spectrum whether the light passes through the grating or is reflected from its ruled surface.

FIG. 39

Scheme of the Spectroscope. Light passes through the narrow slit S which is placed at the focus of the lens A. Parallel rays of mixed colors thus fall upon the prism. The various wave-lengths are refracted differently in the prism and are focused at different points by the lens B. Multiple prism systems serve to increase the separation (see Fig. 23 and Plate 21). When an eyepiece is used to examine the spectrum, the instrument is a *spectroscope;* when a photographic plate is used, it is a *spectrograph.*

The spectroscope is primarily an instrument for analyzing chemical compounds, whether in the laboratory or in the sun, stars or nebulæ. So sensitive is a good spectroscope that quantities of elements much too small to be detected by any other means are plainly revealed by it; hence spectroscopes are in constant use in chemical and physical laboratories, not only those of the great research institutions, but industrial laboratories also. The spectroscope presides over the purity of metals

and other materials used in daily manufacture, guarantees the purity of foods, paints, flavors and extracts, and under proper circumstances reveals even such tiny quantities as the amount of "heavy water" in a sample of ordinary water (about 1 part in 5,000).

In the beginning, astronomers used the spectroscope just as chemists and physicists did: to reveal chemical composition—that of the outer envelope of sun and stars. But other uses were soon discovered. One of the most interesting is the determination of rapid motions of stars and galaxies in the line of sight, first suggested by the English astronomer Huggins. It depends on the fact that when an object emitting light is coming toward the eye, the waves will seem somewhat shortened, hence the light will appear bluer. On the other hand, if the emitting body is retreating, the waves will appear to be pulled out longer, and the light will appear redder. This is known as the "Doppler effect."

Now these differences are of course very slight, and wholly undetectable with the unaided eye. The spectroscope not only reveals them but also provides a method of calculating the velocity toward or away from the observer.

When light comes to the spectroscope from a body at rest with respect to the line of sight, the Fraunhofer lines of the spectrum will all fall in certain places in the spectrum which have been well established by long study. The normal spectrum, as found by observing incandescent elements in the laboratory, the spectrum of the sun, or more usually the spectrum of a single element such as titanium, serves as a pattern for comparison. If light from a rapidly approaching body falls upon the slit, the pattern of lines will be shifted bodily toward the blue end of the spectrum, as compared with the lines of the comparison spectrum. Conversely, if the source of the light be a body in rapid motion away from the observer, the pattern of lines will be seen to have shifted toward the red end of the spectrum.

The amount of the shift reveals the speed at which the body is moving, and the direction of the shift shows whether it is advancing or retreating.

In a random universe it is probable that there will be relatively few stars moving directly toward or away from the observer, just as there will be relatively few moving absolutely at right angles to the line of sight. The true direction of stars and their velocities can be determined, however, by combining the evidence of the camera with that of the spectroscope. If a star is shown by the spectroscope to be approaching at a certain velocity, and photographic records of its position over a period of time reveal that it is also moving perpendicularly to the line of sight at an equal velocity, the star is actually moving in a path at 45 degrees to the line of sight. Moreover, plane geometry shows that it is traveling at a velocity equal to the square root of the sum of the squares of the observed velocities.

Observation of a great many stars in this double fashion (both with the camera and the spectrograph) has given data from which the various motions of thousands of our neighbors in space have been determined. But obviously the method calls for care and patience. The stars are many, and the measurement of their proper motions requires long hours of exacting and tedious work.

To hasten it, Professor R. W. Wood, of the Johns Hopkins University, has proposed a wholesale method of plotting stellar motions. He suggests placing over the telescope aperture groups of small diffraction gratings in such position that the spectra of a number of stars can be photographed at once, with the image of each star alongside its corresponding spectrum.

Another method, reported favorably by Dr. Henry Norris Russell, utilizes a thin cell containing a solution of neodymium salt, placed before the photographic plate. This substance has some remarkably sharp absorption bands in the blue and violet. By comparing the positions of these bands with the stellar lines, any shift due to radial velocity of the star can be detected simply and quickly.

V

In the year 1889 the famous Professor Pickering of Harvard Observatory turned his spectroscope on the bright star Mizar, at the angle of the handle of the Big Dipper, and found, to his surprize, that the spectroscopic lines were double. After some thought he correctly concluded that this was evidence that the star itself is double, tho even in the most powerful telescopes it appears as a single star. The doubling of the spectroscopic lines may be attributed to the fact that one component is advancing in the line of sight, the other retreating; hence the one is shifted slightly to the red, the other to the blue.

As the rotary motion of such a double continues, the lines gradually separate (Plate 13) until their maximum radial velocities are reached; then they converge again, pass through each other, and separate in the opposite direction. Through this phenomenon the spectroscope opens up a new field of usefulness. It can be made to detect the presence of binary systems too close together to be resolved by the telescope, reveal the velocities of the components of such doubles in their orbits, their periods of revolution and their masses.

In the Fourth Spectroscopic Catalog, published in 1936 by the Lick Observatory, 1,400 spectroscopic binaries are listed, and the orbits of 404 stars calculated. About one star in every five examined with the spectroscope was found to have a variable radial velocity, indicating motion around a center, and probably denoting that it is part of a binary system of which the other partner may be dark or at least too faint to be detected.

When stars are examined spectroscopically it is found that there are a great number of kinds, but most of them can nevertheless be classified into six general types. They are thus classified in the greatest of the modern star catalogs, the Henry Draper Catalog, named for the American astronomer who did so much toward the development of stellar photography. This catalog was compiled at Harvard Observatory and contains data on the enormous number of 225,300 stars, ranking from the very

brightest down to about the ninth magnitude, or three magnitudes fainter than the faintest star visible with the unaided eye.

The catalog, of course, gives the position of each star, the photographic and "photovisual" magnitudes of each, and the spectral type. It is the latter to which astronomers refer in studying the "age" or "evolution" of stars, for the six general types may be interpreted as six stages in evolution from large, hot, very bright stars to burned-out dwarfs. The great majority of stars fall readily into these six classes, which are denoted by the letters B, A, F, G, K and M, and each different spectral type is associated with a specific color for the star.

In color the series begins with the bright blue stars, like Rigel, and passes successively through white stars, like Sirius; pale yellow, such as Procyon; yellow, like the sun; reddish, as Arcturus; and definite red, of which the giant star Betelgeuse is typical. Examined according to spectrographic appearance, even more striking differences appear. The type-B stars, like Rigel, show few absorption lines, and these are mainly of hydrogen and helium, with oxygen and nitrogen lines showing less conspicuously. In the next group, the white A stars, hydrogen lines predominate. The helium lines conspicuous in the preceding type do not appear, but lines of metals come in faintly. In the pale yellow F stars, to which group Procyon belongs, metallic lines are conspicuous, especially lines similar to those produced when metals are excited to emit light in an electric arc.

When we come to the G stars, the group of our sun, the metallic arc lines are predominant, mingled with others such as those produced when metals are excited by a very hot flame to emit light. Stars belonging to this group are, like those preceding, still in a gaseous state and very hot, but pronounced cooling nevertheless has taken place. In the next type, K, cooling is even more evident, for here begin to appear the spectral lines of chemical compounds as well as those of excited atoms and ions. Flame-type lines are pronounced, tho the arc lines are still strong. Finally, in the M type the flame lines predominate. Heavy bands attributable to molecules appear and often are a

conspicuous feature of the spectrum. The most pronounced molecular lines are due to titanium oxide.

Together with the different spectral types there is associated a gradual reduction in mass; a phenomenon to be expected on the theory that the stars in the series are progressively older, and have radiated away large portions of their substance in the process. But in the M stars this rule is abruptly inapplicable. Investigation has shown, indeed, that there are two types of M stars, giants like Betelgeuse, which are probably larger than any other type, and small red stars, or dwarfs, of which there are many striking examples in the heavens. Hence it may be assumed that the giant red stars are not in the same stage of evolution as the dwarfs at all; they may represent a class, in fact, younger even than the blue type-B stars. If the spectral classification really does indicate the age of stars and the direction of their growing old, our sun is already well on the way toward dwarfism, being in the G stage of evolution and rapidly approaching the reddish K type typified by Arcturus.

The spectroscope thus not only indicates the ages of the stars, but also reveals the condition of our sun and its relative place in time. Moreover, through direct studies of the sun, the spectroscope and various special instruments that have branched from it have revealed a great deal about the nearest star—facts that have applications here on earth and in our daily lives, in that they reveal, or are beginning to reveal, the reasons for weather changes, the mysterious aurora, the magnetic storms and many other things.

VI

Chief among the "children" of the spectroscope and spectrograph are the *spectrohelioscope* and *spectroheliograph*. These instruments differ from each other in the same manner as the spectroscope differs from the spectrograph; one is used in conjunction with the photographic plate, the other directly with the eye. But there are certain other differences too.

The spectroheliograph (which was the first of the two invented) was devised by Dr. George Ellery Hale, first director of Mt. Wilson Observatory and one of the foremost observers of solar and stellar phenomena of our time. In principle it is a spectrograph, with certain important additions.

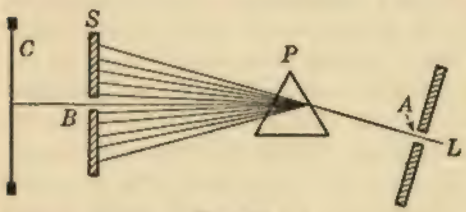


FIG. 40

Scheme of the Spectroheliograph. A beam of sunlight L enters the slit A and falls on the prism P, where it is broken into the spectrum S. A second slit, B, lets the light of a single band through to the photographic plate C. When the whole instrument is moved with relation to the plate, an image of the sun will be formed on the plate, in monochromatic light of only one element in the sun's envelope. (In this diagram the lenses, which are like those of the spectrograph (Fig. 39), have been omitted for simplicity.)

When bright light, such as sunlight, enters the slit of the spectroscope and falls upon the prism, a band of bright colors is the result, marked by the series of vertical lines of which Fraunhofer found more than 600 in the solar spectrum. As we have seen, these lines indicate the presence of specific elements in the outer envelope of the sun.

Now, if a second slit is interposed at the spectrum, and so arranged that it admits the light falling on only a single one of the lines, the light passing through the second slit will be only that from a single element in the sun's outer envelope (Fig. 40). Suppose, for example, that a line such as Fraunhofer's K line of the element calcium is chosen, and the light from part of the sun's face passing through the second slit is allowed to fall on a photographic plate. The image recorded there will be a picture of that small portion of the sun made with *calcium* light. If the first and second slits are now moved across the sun's disc, the photographic plate remaining stationary, a complete picture of the disc, photographed in calcium light, will be built up of the successive images of portions of the sun's face which have passed through the first slit, the prism and the second slit.

Pictures taken in this way yield curious and important information, for they show the distribution of the various elements across the sun's disc. Calcium, for example, is found to lie in interesting cloud-like formations, called *flocculi,* especially in the vicinity of the sun-spots (Plate 26). Spectroheliograms of the sun taken with the red light of hydrogen (that is, with one of the lines of the hydrogen spectrum that lies in the red part of the spectrum) show magnificent "cyclones" of this element apparently whirling about the sun-spots in gigantic storms, and being spumed upward from the sun's surface thousands and sometimes hundreds of thousands of miles. With the spectroheliograph these solar prominences can be photographed at any time. It is no longer necessary to wait for an eclipse to study these magnificent phenomena of the sun.

The spectrohelioscope is a visual adaptation of the principle of the spectroheliograph; it enables the astronomer to see directly what is going on in the sun. If a narrow slit is cut in a large piece of pasteboard, and we look through it at an electric light bulb, only a portion of the bulb will be visible, for the aperture will not be wide enough to admit the entire image. If now the slit is oscillated rapidly at a suitable distance from the eye, moving back and forth far enough at each oscillation to cover the entire width of the lamp, the effect will be that of a complete image. This is due to the persistence of the sensation of light on the retina of the eye, a phenomenon taken advantage of in motion pictures.

If the eye instead of a photographic plate is placed at a suitable distance behind the second slit of a spectroheliograph, and the whole apparatus then oscillated rapidly as in the case of the experiment with the cardboard slit, the whole image of the sun will be revealed in monochromatic light from hydrogen, calcium or any other element chosen.

This instrument, also the invention of Dr. Hale, permits direct interpretation of many of the phenomena shown statically by the spectroheliograph. The whirls of hydrogen are seen to

move; the prominences fly outward from the disc. And by an attachment applicable both to the spectroheliograph and the spectrohelioscope, the instrument can be caused automatically to admit light due to shifts either to the red or blue, permitting examination of gases in motion in the line of sight, flying at high velocities outward from the sun toward the earth, or falling back again.

Recently astronomers have been able to capture on motion-picture film the unforgettable sights to be seen through the spectrohelioscope. At the McMath-Hulbert Observatory, part of the University of Michigan, motion pictures of the sun's activities are being taken with the aid of an instrument bearing the formidable name of *spectroheliokinematograph*—a spectrohelioscope with a moving-picture camera at the eye-end.

VII

None of these instruments, however, reveals the delicate traceries of the sun's corona, the beautiful brilliant veil of light seen during total eclipses. This is completely blotted out by the brilliance of the other parts of the sun, and until recently there was no way by which it could be seen except at total eclipse. Theoretically the corona should be observable in daylight, since it stands out away from the sun for great distances; but it is so faint as compared with the sun that the coronal light is completely lost. Diffraction in our atmosphere produces a halo 1,000 times brighter than the corona around the image of the sun's disc.

In 1933 a new instrument, called the *coronagraph,* was described by the French astronomer Bernard Lyot in the Journal of the Royal Astronomical Society of Canada. It had previously been in use in France and at Mt. Wilson Observatory, where it was found to perform with success. At the International Astronomical Union at Stockholm in 1938 Dr. Lyot provided one of the most noteworthy communications of the session, describing his method and exhibiting the sharp photographs obtained.

In the Lyot coronagraph (Fig. 41) the light of the corona is sifted out after passing through elaborate apparatus designed to

produce, in effect, an artificial total eclipse. The sun's light is passed through a diaphragm *A,* and a lens *B,* and brought to a focus on the blackened brass disc *C,* which extends just a trifle beyond the image of the sun all around the edge. It is here that the "eclipse" is made. The coronal light passes the disc, and falls on the lens *E,* which produces an image of lens *A* on the diaphragm *F,* in the center of the opening of which is a tin screen *G,* the purpose of which is to stop the light of the solar image formed by reflection between the two surfaces of the lens *B.* Thus freed of all diffuse light and all light coming from the body of the sun proper, the light of the corona is passed on to the aprochromatic objective *H,* which forms at its focus an achromatic image of the corona. If a photograph is desired, it can be taken at the focus of *H,* with the aid of a red filter and panchromatic plates.

More recently another promising method of studying the corona in full daylight was developed by A. M. Skellett, of the Bell Telephone Laboratories. Mr. Skellett's idea is to scan the image of the sky around the sun by moving rapidly across it a disc containing a small hole, behind which a photoelectric cell has been placed. The resulting photoelectric current will be made up of high-frequency components due to the details of the coronal image. These currents can be reconverted into light and enlarged upon a screen by methods known to television engineers. The various components of the current produced in the scanning can be separated by appropriate electrical filters, and only those arising in the corona permitted to appear in the reproduction of the image.

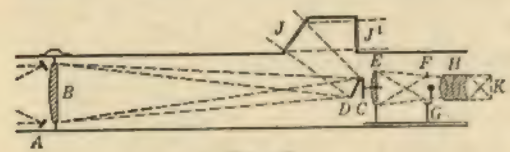


FIG. 41

How the Lyot Coronagraph Reveals the Corona. The light passes through the diaphragm A and the lens B, which casts an image of the sun on the disc C. This causes an "artificial eclipse." D reflects the heat out of the instrument. The image of the corona passes C, falling on the lens E, which focuses it through the diaphragm F on the achromatic lens H, which casts an image of the corona at K.

VIII

We have yet to consider other highly important instruments which bring us details of what is happening in the sun. They are the *bolometer,* devised by the late Dr. S. P. Langley of the Smithsonian Institution, and the *pyrheliometer,* invented independently by Sir John Herschel and the French physicist C. S. M. Pouillet, about the year 1830. Both of these instruments have since been much improved at the hands of Dr. C. G. Abbot, secretary of the Smithsonian Institution.

The bolometer is an electrical thermometer. As originally designed by Langley, it consisted of two very thin hair-like ribbons of platinum, blackened with lampblack, and placed fore and aft of a metal plate. The instrument is used with the spectroscope, and is so sensitive that it gives readings of the varying amount of heat in the different lines of the solar spectrum.

The contrivance is so arranged that a portion of the spectrum falls on the foremost, exposed platinum wire, but not on the second, hidden behind its metal shield. The tiny difference in temperature thus produced is sufficient to alter the balance of an electrical circuit of which the apparatus is a part. This moves a small mirror, less in diameter than a pinhead. A shaft of sunlight playing on the mirror is deflected across a moving photographic plate, which thus records the warming or cooling of the exposed ribbon of platinum. The instrument is so sensitive to temperature changes that a difference of a millionth of a degree will cause an appreciable deflection of the ray of light.

As the spectrum of the sun is moved over the bolometer by clockwork, a jagged line called a "solar energy curve" or a "bolograph" results. The high points of the line represent warm parts of the spectrum, the low spots relatively cooler ones. As the spectrum is moved, the instrument will continue to register far beyond the last visible light of the red end, and gives a measure of the heat energy contained not only in the visible parts of the spectrum, but also in the invisible light.

Bolographs show the sun's surface temperature to be about

6,200 degrees Centigrade on the Absolute scale, or approximately twice as hot as the electric arc.

The *total energy* derived from the rays of the sun is measured by the pyrheliometer. As devised by Pouillet, it consists of a small flat tank of water held toward the sun, the top or sun-side being blackened with lampblack to absorb the rays. Out of the lower side projects a thermometer, on which the rise in temperature of the water in the box can be read. Since the area of the sun-side of the box and the amount of water it contains are known, the rise in temperature can be measured directly in calories per square centimeter per minute, a calory being the amount of heat required to raise the temperature of one gram of water one degree Centigrade. In some forms of the apparatus a second disc is placed around the neck of the thermometer (Fig. 42) to help keep the bottom of the water box directed properly at the sun, the adjustment being such that the shadow of the box always just covers the lower disc.

A much more efficient and accurate pyrheliometer, tho working on the same principle as that of Pouillet, was devised by Dr. Abbot. It consists of a blackened disc of silver, in which is embedded a bent-stem thermometer. The light of the sun is admitted to the silver disc through a cylindrical vestibule which can be closed by shutters. The device is mounted on an equatorial axis and driven by clockwork to keep up with the sun.

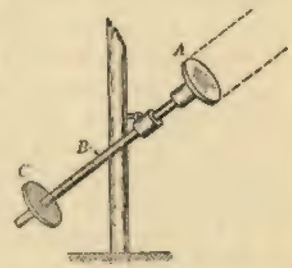


FIG. 42

Pouillet's Pyrheliometer, One Type of Apparatus for Measuring the Heat of the Sun. The sun heats water contained in the disc-like box A. The heat is recorded on the thermometer B. The disc C helps to keep the contrivance properly oriented.

The pyrheliometer reveals that there is considerable variation in the amount of radiation received from the sun. The sun-spots are partly responsible, as well as the earth's atmosphere and other factors. The average is usually more than one calory per minute per square centimeter on the earth's surface at sea level, and would

be nearly two calories per minute per square centimeter were it not for the absorption of the air. If it were possible to transform all the heat that reaches the surface of the earth into mechanical work, it would amount to more than a horsepower per square yard. No inventor has as yet succeeded in capturing more than a small fraction of this energy.

IX

Measuring the heat of the stars requires an instrument even more sensitive than the bolometer. For this work astronomers now have recourse to the *thermocouple* (Plate 21), thanks in great part to the developmental work done a few years ago by Dr. W. W. Coblentz and his associates of the United States Bureau of Standards and the more recent improvements introduced by Dr. Edison Pettit and Dr. Seth B. Nicholson of Mt. Wilson Observatory.

When two bars or strips of dissimilar metals are welded together at their ends, and one joint is heated more than the other, a current will be caused to flow in the circuit. It can be measured by a sensitive galvanometer, and is always proportional to the difference between the temperatures of the two joints.

This is the principle of the thermocouple, and under proper conditions it is a sensitive instrument indeed. Thermocouples constructed for stellar research by Dr. Pettit and Dr. Nicholson, and used with the 100-inch telescope at Mt. Wilson, were sufficiently sensitive to detect the heat of a candle 100 miles away. With such an instrument the investigators were able to measure the heat radiation of stars down to the thirteenth magnitude, which are less than 1/600th as bright as the faintest star that can be seen with the unaided eye.

This achievement becomes all the more impressive when it is realized that a star of the sixth magnitude, the faintest visible without a telescope, radiates upon the whole United States no more heat than the sun radiates upon one square yard of surface. Yet, in the case of such a star, the thermocouple will show that the increase in heat on account of it is one-half of

one-millionth of a degree Fahrenheit. The electric current generated thereby is about one twenty-billionth of an ampere.

The arrangement of a stellar thermocouple is shown diagrammatically in Fig. 43. The two thin strips of metal, *A* and *B*, are joined at their ends at *C* and *D*. Across the top of each union is fastened a blackened disc (*E* and *F*) which catches and absorbs the radiation received, transforming it into heat. The strip *B* is broken to let the delicate galvanometer *G* into the circuit.

When the disc *E* catches more energy from the image of a star than *F* does from the image of a starless portion of the sky, *C* will become warmer than *D*, and a current will flow in proportion to the difference in temperature of the two joints. This will deflect the needle of the galvanometer. In studying the surface of a large body, such as the moon, the two discs can be placed at different parts of the image in the telescope, and the readings will show how the temperature varies in adjacent areas of the body. The direction of current flow in such a case indicates which of the joints is the warmer.

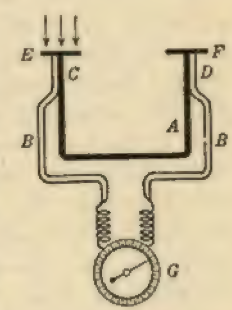


FIG. 43

Scheme of the Thermocouple. The metal strips A and B are welded together at their ends C and D, and these in turn are covered by the blackened discs E and F. If one of the joints is heated more than the other, a current of electricity will flow through the circuit, deflecting the needle of the galvanometer G.

For stellar work the sensitivity of the apparatus is much improved by placing it in a vacuum; this was one of the contributions of the United States Bureau of Standards experiments. Many different metals have been tried for the dissimilar strips, including antimony, bismuth, copper, gold, platinum and tin. Drs. Pettit and Nicholson found the most satisfactory combination to be a strip of bismuth and one of bismuth alloyed with 5 per cent of tin.

It will be noted that the thermocouple measures the *total radiation* of celestial bodies, not merely the heat. By using

screens or filters of various substances which transmit only certain wave-lengths of light, thermocouple readings for the spectra of the stars similar to the bolographs of the sun may be obtained. The temperature of the surfaces of the stars can also be learned. Drs. Pettit and Nicholson determined that they range from 23,000 degrees Centigrade on the Absolute scale (about 41,000 degrees Fahrenheit) for the very blue stars such as *Zeta Orionis,* to 6,000 Centigrade Absolute (10,000 degrees Fahrenheit) for stars like the sun, and 1,800 degrees Centigrade Absolute (2,800 degrees Fahrenheit) for the very long-period variable stars such as *Omicron Ceti.*

X

We come now to an instrument entirely different, both in principle and application, from any previously described—an instrument so sensitive that it can be used to measure a distance smaller than a wave-length of light, yet one that reaches out into the abysses of space and takes the diameter of stars.

It is the *interferometer,* developed and brought to its present state chiefly by the late Dr. Albert A. Michelson. It was an interferometer that Dr. Michelson used to make his famous test of the "ether drift," the negative result of which, incidentally, was an important stepping-stone in the development of the Einstein theory. Improved forms of the interferometer were later used by Michelson and his successors to refine the measurement of the speed of light. In 1920 Michelson, working with Dr. F. G. Pease at the Mt. Wilson Observatory, succeeded in measuring the diameter of the great star Betelgeuse (the brightest star in the constellation of Orion) with an interferometer applied to the 100-inch reflector.

The interferometer splits a beam of light into two parts, which are caused to follow separate paths until they are brought together again. When they are returned to a single beam a curious phenomenon known as an *interference pattern* appears. Its arrangement depends on the difference in length of the paths the beams have taken, or the nature of the substances through which they have passed.

Assuming, for simplicity, that the original beam was monochromatic, if the separate components of the beam passing through the interferometer take paths exactly equal in length, and other factors do not enter, the beams will be fused again without any visible change in brightness. But if the path of one of the divided beams is half a wave-length shorter than the other, when they fuse the troughs of the waves of one will coincide exactly with the crests of the waves of the other. The result will be a cancellation, or darkness. Such "interference" may be observed in many types of wave motion, including sound.

The light of a star comes to us from such a tremendous distance that even in the most powerful telescopes its source seems to be a point. Actually the various rays of the beam originate from points as far apart as the diameter of the star. Michelson's stellar interferometer caused the interference of beams from opposite sides of a star to reveal the distance between their points of origin.

Across the top of the 100-inch telescope he placed a stiff steel girder twenty feet long. On this were mounted four mirrors, each set at an angle of forty-five degrees, and so arranged that light falling upon the outer mirrors was transmitted to those nearer the middle, and from them directed downward to the speculum of the huge telescope. The central mirrors were separated by a distance approximately equal to the diameter of the speculum. The two outer mirrors were mounted in such fashion that they could be moved symmetrically out or in along the girder.

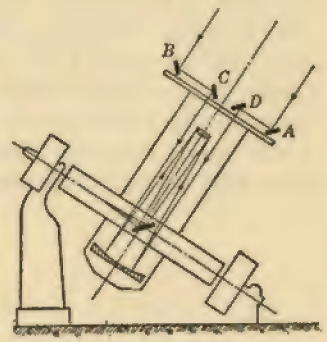


FIG. 44

The Path Taken by the Light of a Star in the Interferometer. The beams strike the movable mirrors A and B, and are sent respectively to mirrors D and C, thence downward to the mirror of the telescope.

When light from Betelgeuse fell upon these outer mirrors it was transmitted through the secondary mirrors to the telescope (Fig. 44), and appeared in the eyepiece as a beautiful light and dark pattern of interference fringes. Slowly the small mirrors were moved outward toward the ends of the girder until a point was reached at which the interference practically disappeared, giving a pattern of almost uniform brightness. When this point was reached (at a separation of the small mirrors of about 10 feet), the application of a fairly simple mathematical formula revealed the angle subtended by the diameter of the star as seen from the earth. This proved to be the almost inconceivably minute value of .046 second of arc.

The star's distance had already been determined by other methods, and it was a simple matter to calculate the diameter of Betelgeuse. It came out 270,000,000 miles. No wonder this star is known as a *giant!* If our sun were the size of Betelgeuse, the planets Mercury, Venus and the Earth would be completely engulfed in it. The outer edge of the body would almost touch the orbit of Mars.

The stellar interferometer has since been used to reveal the diameters of other stars, and tho it can probably give good results only with the brighter ones, nevertheless it has already extended our knowledge of the stellar universe, and will extend it still more. A stellar interferometer fifty feet in length, complete with its own telescope, is now in operation at Mt. Wilson.

PART III

ASTRONOMY'S MARCH CONTINUES—THE INSTRUMENTS OF TODAY

Chapter XIII

HOW TELESCOPES CAME TO AMERICA—OUR HISTORIC OBSERVATORIES

I

IN the year 1832 the British astronomer George B. Airy, later to become Astronomer Royal, closed a report to the British Association with the faintly patronizing remark that, as for the United States, he did not know of the existence of a single public observatory in the whole country.

Interestingly enough, it was not America's progress in astronomy but Airy's information that was at fault. A full seven years earlier, in 1825, Dr. John Caldwell, president of the University of North Carolina, had set up some instruments in his lecture room, had used them to determine the latitude and longitude of Chapel Hill, and astronomy in America was on the march.

From this promising beginning, the University of North Carolina proceeded, in 1831, to build a real observatory—apparently the first in the United States. The year before, it is true, professors at Yale had set up a telescope in the steeple of one of the college buildings at New Haven, but the low windows of the room interfered with the use of the instrument and some time elapsed before a real observatory was built at Yale. The honor therefore of leading that triumphant procession which has culminated in such dinosaurs among observatories as Yerkes, Mt. Wilson and Mt. Palomar goes to Dr. Caldwell, an obscure and now all-but-forgotten college president, whose yearning to study the heavens was so great it nearly wrecked his budget.

The story of the first American observatory gives us a reveal-

ing glimpse into the trials of an intellectual pioneer in a new land. Filled with zeal for its success, Dr. Caldwell went to Europe in 1824 to buy equipment for the new North Carolina university. He had some $7,000 all told. Of this amount he laid out $3,234.74 for books and $3,361.35 for apparatus—not a bad balance, except that virtually all of the "apparatus" consisted of astronomical instruments.

And Dr. Caldwell was certainly no piker. His purchases included a transit instrument by Simms of London, of aperture 3 inches and focal length 44 inches; an altazimuth telescope, also by Simms, of 2½ inches aperture and 52 inches focal length, made by Dolland, and an astronomical clock made by Molyneux. Lesser equipment included a sextant and a Hadley's quadrant. Of all these, the altazimuth instrument was the best, and beautifully mounted. Its horizontal and vertical circles were twenty and twenty-four inches in diameter respectively, with two verniers and reading microscopes for each. The circles were graduated on platinum bands to 5 minutes of arc.

The telescopes arrived in the winter of 1825-26. Dr. Caldwell unfortunately had not provided space to mount them. They were first set up in the college building, but this soon proved unsatisfactory. Perceiving this fine investment going to waste, the college was at length induced to appropriate money for the construction of a separate observatory. The foundations of the structure were laid in April, 1831, and it was completed in August, 1832. It contained but a single room, the building being fifteen feet wide, twenty-three feet long and about twenty-five feet high. The first eight feet of the walls were of stone, plastered inside and out, and enclosing a low basement slightly excavated. Above this the walls were of brick, terminating in a parapet around the top.

The first floor was several feet above the ground, and was reached by a flight of steps on the eastern face of the building. The roof was a nearly flat double-door, caulked and pitched. Two pillars of masonry rose through the interior, one of them terminating just above the first floor and bearing the transit instrument; the other rising above the roof, with a place at the top where the altazimuth instrument could be placed. To furnish range for the transit, which was inside the building, a slit was made across the roof and down into the north and south faces of the walls. Shutters were constructed to close it up when the transit was not in use.

Such was America's first observatory building. It cost $430, and was unlucky from the start.

It had hardly been completed when Dr. Caldwell's health began to fail. Imperfections in the workmanship and materials of the building began to appear. Bricks crumbled and planks in the flat roof swelled and shrunk. The joints were soon anything but watertight. It became necessary, after Dr. Caldwell's death in January, 1835, to remove the instruments. The building then went rapidly to decay, fell victim to fire about 1838, and thereafter was a crumbling ruin on the campus for several years, until the last traces of it were finally removed.

When the Yankee soldiers seized and occupied the university in 1865, they found some of Dr. Caldwell's instruments stowed away in an attic. The instruments were all quite useless for astronomical work by that time, but some of the members of the faculty, fearing the possibility that they might be robbed, had hidden watches and other valuables in the tube of the transit. The valuables were taken. The instruments also disappeared.

II

The telescope for Yale College was ordered in 1828 and received from England in 1830. Yale University Observatory may therefore assuredly lay claim to being the first *permanent* observatory in America.

Soon there were others. In 1834 Professor Albert Hopkins of Williams College went to Europe to select instruments for an astronomical observatory at that institution, and his observatory was ready for use in June, 1838. In 1830 a depot of charts and instruments was established at Washington by the United States Navy, under the direction of Lieutenant L. M. Goldsborough. Among the functions of this depot was the ascertain-

ing of errors and rates of ship chronometers, accomplished by means of sextant observations; a small nucleus from which later developed the United States Naval Observatory.

Here and there colleges began to have dreams of observatories that would rival even the mighty ones of Europe. And suddenly one of them did. Despite the various preludes, the real story of American astronomy opens at Cambridge, Mass., where in 1839 the Harvard Observatory was founded. At the beginning it gave no outward sign of its coming greatness. The first director wasn't even an astronomer—he was a manufacturer. No one would have thought, when the relatively obscure Cornishman William Cranch Bond took over the duties of astronomer, that Harvard Observatory would presently be attracting attention even in Europe, where men of science were still inclined to look upon America as a land of unscientific barbarians.

Bond began his work in a Harvard Observatory that consisted of a single small building. Within eight years he had stirred up such a reputation that funds were forthcoming for better instruments and more ample accommodations. By 1847 Harvard Observatory was housed in a new building, and what was more, had one of the largest telescopes in the world, a refractor of size identical with that installed at the same time in the famous Russian Imperial Observatory at Pulkowo.

This telescope was a 15-inch made by Merz and Mahler of Munich. A year after it was installed William Cranch Bond's soon-to-be-famous son, George Phillips Bond, discovered the eighth moon of Saturn, and in 1850, using the same instrument, the elder Bond discovered, simultaneously with the Reverend W. R. Dawes in England, the inner or "crepe" ring of that planet.

The 15-inch refractor was, later, to take part dramatically in many another observational venture, and most especially in the development of photographic astronomy, which made Harvard Observatory and its astronomers world-famous. It was with this telescope that George Phillips Bond succeeded, in 1850, in obtaining the portrait of the first star ever photographed; with the 15-inch he carried on the long series of photographic experiments that helped establish celestial photography in this country.

The 15-inch also figured—in a curious left-handed way—in launching the telescope-making industry in America. Alvan Clark, later one of the most important telescope-makers in the world, relates in his autobiography how, although interested in making telescopes, he nevertheless had been discouraged by the difficulty of giving perfect curvature to the lenses of refractors.

Finally he obtained permission to look through the 15-inch refractor at Harvard. That look marked the turning point in his career. "I was far enough advanced in knowledge of the matter to perceive and locate the errors of figure in their 15-inch glass at first sight," he reports none too modestly in his autobiography. "Yet these were very small, just enough to leave me in full possession of all the hope and courage needed to give me a start, especially when informed that this object-glass alone cost $12,000."

The 15-inch glass, despite its "errors of figure" (which were very slight indeed) was a notable and useful telescope. It would still be doing active duty today were it not for the fact that it was figured for the visual rays of light, whereas astronomy has now little need of any but photographic telescopes. For eighty-five years it was a major instrument in the program of the observatory, the nucleus around which the great institution of today grew. It now reposes, an honored veteran, under its dome in Building A, at Cambridge.

III

Harvard today ranks among the dozen foremost observatories in the world. Its stations are located on two continents; its collection of photographs is the most complete on earth; it is the gathering-place of astronomical knowledge in this country and the central station through which other observatories are kept in touch with discoveries.

One of the most notable astronomers of our time, Dr. Harlow Shapley, is the director. In addition to the main observatory at

Oak Ridge and Cambridge, Harvard operates the solar observatory at Climax, Colorado, and a station at Harvard Kopje, on the high plateau of the Orange Free State, South Africa, not far from Bloemfontein.

The old building at Cambridge is no longer used for observation; the encroachment of the city has made the seeing too poor in that locality. Instead, under its roof are data from two continents gathered for reduction and preservation. Here are stored in steel vaults more than 450,000 photographic plates, a wealth of astronomical material that represents records of the appearance of the skies of the northern and southern hemispheres over long periods of time. Among them are thousands of spectra taken with objective prisms on various telescopes, the enormous treasure-house which furnished the data for the spectral classifications of the famous *Henry Draper Catalogue* and its *Extension*. Here also are the large-scale, long-exposure plates taken with the 24-inch Bruce doublet in an extensive survey, still in progress, of the faint extra-galactic nebulae.

In the old observatory is also to be found the headquarters of the American Association of Variable Star Observers, an organization of professional and amateur astronomers which, in conjunction with foreign societies, brings in a continual stream of information about variable stars from a network of observers located in practically every part of the earth.

The plan for opening a southern station for Harvard was developed in the '80s of the last century, and was made possible by a grant of funds from the late Uriah A. Boyden. At first a site was selected at Arequipa, Peru, but despite the altitude (more than 8,000 feet), the seeing at Arequipa proved less satisfactory than had been expected. The entire observatory was moved in 1927 to the present site near Bloemfontein. Work there is carried on under the direction of Professor J. S. Paraskevopoulos, with a new 60-inch reflecting telescope and four refractors, ranging in aperture from 24 inches down to eight. The 60-inch has optical parts by J. W. Fecker, and a modified Cassegrain arrangement similar to that of the 60- and 100-inch telescopes at Mt. Wilson Observatory.

In addition to this equipment, the South African station has cameras equipped with the three-inch lenses developed by Professor Frank E. Ross of Yerkes Observatory—lenses so well adapted for wide-angle photographic work that pictures made with them of such difficult subjects as the Milky Way can not be equaled with any other type of equipment.

The Oak Ridge station is the newest part of the observatory, and was first used in 1933. The increase in telescope equipment of the institution, as well as the growing northward trend of the city of Cambridge, made it imperative to select a better site and one with more space for instruments. Oak Ridge is twenty-seven miles northwest of Cambridge, in the Town of Harvard. The new observatory station stands in the midst of a tract of nearly forty acres of wooded land, guaranty against the too close approach of such neighbors as might, with lights, smoke or vibration, disturb the seeing.

Using the observatory's two large reflecting telescopes, of 61 and 24 inches respectively, seven photographic refractors, ranging in aperture from 16 inches to one inch, and four visual refractors, of which the largest is the famous 15-inch, Harvard astronomers in Massachusetts are engaged in one of the most ambitious attempts to map, study and penetrate the mysteries of our galaxy ever undertaken. They have discovered, among other things, several "windows" or open spaces in the Milky Way, through which it is possible to see and photograph the galaxies beyond. One window, in the region of the constellations Perseus and Cassiopeia, is a break in the veil of cosmic dust that obscures the heavens beyond the rim of our own stellar system. Through the hole, Dr. Shapley recently reported, Harvard astronomers have already counted the staggering total of 6,000 new galaxies, each composed of thousands of millions of stars as large as our sun, or larger. In addition, there have been photographed six clusters of galaxies—super-systems of stars revealing higher orders of the universe.

Another line of investigation under way at Harvard is that of measuring the distance to which our own island universe extends into the depths of space. These measurements are made

toward the "anticenter," the point opposite the supposed center of the galaxy's rotation.

"This very tedious investigation," Dr. Shapley reported in 1938, "has not as yet progressed far enough to give more than the preliminary indication that the galactic system extends at least 10,000 parsecs in the direction opposite the center."

Since a parsec is 3.26 light years, or 19,560,000,000,000 miles, it is clear that it is no small galaxy the Harvard astronomers are examining; it is no small system in which our earth and our solar system play their insignificant part.

IV

So poor was the Congress of the United States in astronomical imagination a century ago, the first *national* observatory in the United States had to be built at private expense.

The United States Naval Observatory today compares in work and astronomical standing with the great Royal Observatory at Greenwich, of which it is the American equivalent, but it had its beginnings as a depot of charts and instruments, and a place where ships could have their clocks set right. It was still nothing more when, in 1833, Lieutenant Charles Wilkes, famous for his exploits as an explorer and scientist, was put in charge. Political quarrels and procrastination for more than ten years had prevented Congress from acting favorably on the establishment of a real Naval Observatory, so Lieutenant Wilkes dug into his own personal bank account, laid out plans for an observatory, and in 1834 hired workmen to put it up.

His money was limited, so the building was a small one—only sixteen feet square. In it he mounted with meticulous care a transit made by the English optician Troughton, who had constructed it nineteen years earlier for the Coast Survey. With this instrument Lieutenant Wilkes clocked the stars at their transit night after night for three years. Valuable data began to emanate from the strange little Naval Observatory. The country became interested. At last, in 1842, the Secretary of the Navy was authorized to contract for a suitable new building,

to be used both as a depot of charts and instruments, and an observatory.

But by that time Lieutenant Wilkes, who had set the whole matter in motion, was no longer in charge. He had been succeeded by Lieutenant James M. Gilliss. Gilliss immediately began to make plans for the new observatory. Developing them, he had a very pleasant trip abroad, during which he interviewed distinguished astronomers and telescope-makers. Upon his return he finished the observatory—and a very suitable one it was, too—but had scarcely seen the completion of the structure when he in turn was relieved of command. To Lieutenant Matthew F. Maury, his successor, who took charge in 1844, fell the honor—and opportunity—of laying the foundations for the real work of the Naval Observatory.

He did not scamp the job. No beaver worked harder. He laid out the extensive system of hydrographic work which today provides an important body of information to navigators. He collected information all over the world about ocean currents, wind and air pressures, temperatures and other marine and meteorological data. He made extensive and detailed charts—work that has now in the main been taken over by the Hydrographic Office.

As to astronomy, Lieutenant Maury was an extremely practical man. He instituted at once systematic observations of the sun, moon, planets and brighter stars—work which has continued to this day. The results of the first year's observations were published in 1846, in a book modestly subtitled "the first volume of astronomical observations ever issued from an institution properly entitled to the name of an observatory on this side of the Atlantic."

In that same year the Secretary of the Navy authorized the publication of a nautical ephemeris—a collection of tables for use in navigation showing the calculated positions of celestial bodies from day to day. This was the beginning of one of the institution's most important publications. Now it puts out the *American Ephemeris* every year, and maintains a continuous

series of observations of the sun, planets, moon and certain of the brighter stars for the aid of navigators.

By 1847 the United States Naval Observatory was already becoming internationally famous as a source of accurate data for navigators. Then discoveries of wider scientific import began to be made there. Dr. Sears Cook Walker, a member of the staff, showed that the planet Neptune, discovered by the astronomer John G. Galle at the Berlin Observatory on September 23, 1846, had actually been seen earlier, and had been identified as a star by Joseph J. L. de Lalande in 1795. One result of this discovery was the compilation of data based on Laland's catalog of stars, by which the path of Neptune could be determined.

Between 1854 and 1860 three minor planets were found, despite the fact that the instruments then available were of low power for such astronomical work. In 1865 a new meridian circle was installed, which for the first time enabled the observers to measure right ascension and declination of a star at the same time and with equal exactness.

Five years later this instrumental equipment was augmented by a truly epoch-making telescope. In 1870 Congress authorized the construction of the largest refractor possible of manufacture in America, to cost not more than $50,000.

Alvan Clark, the man who had been encouraged to launch into this work as a result of his glimpse into the great 15-inch refractor at Harvard, was selected to make the optical parts of the giant instrument. With the aid of his son, Alvan G. Clark, he constructed an objective of 26-inch aperture, a lens surpassing any other in the world at that time, both for aperture and perfection of figuring (Plate 23). It was mounted equatorially, and installed in its own room at the observatory in 1873.

From that moment the Naval Observatory became one of the great modern observatories. In 1877, Dr. Asaph Hall discovered with this fine telescope the two small hurrying moons, Deimos and Phobos, of our planetary neighbor, Mars. The instrument was also used by Professor Simon Newcomb, leading American astronomer at the close of the nineteenth century and the beginning of the twentieth. It was at the United States Naval Observatory that Professor Newcomb and Professor George W. Hill accomplished their monumental task of determining the orbits of the moon, Venus, Mars, Uranus, Neptune and Saturn. There also Professor Newcomb and Professor Albert A. Michelson began the epoch-making work of measuring the velocity of light, a labor that is not finished even yet, tho both the original workers are long since dead.

V

The present superintendent of the Naval Observatory is Commodore J. F. Hellweg, U. S. N. (Ret.). Its staff of thirty-eight includes such eminent figures in astronomy as Dr. G. M. Clemence, director of the *Nautical Almanac,* Paul Herget, Harry E. Burton, Chester B. Watts, Paul Sollenberger and F. P. Scott.

The work of the observatory is eminently practical, as befits the national observatory of a practical nation; its operations touch the life of every American. It is at the Naval Observatory, for example, that Standard Time is obtained, the clocks of the country being set according to corrections made in sidereal or star time, which bears a constantly changing relationship to the ordinary time by which we regulate our lives.

Time is obtained by observation of the instant at which certain bright stars cross the meridian near the zenith at Washington. At the Naval Observatory an ingenious new type of instrument has been developed for this work, the "photographic zenith tube." Rigidly fixed in a vertical position, it is unable to photograph any objects except those which pass very near the zenith. At the lower end of the tube is a basin filled with mercury. The light from a star passes through a lens at the upper end of the instrument, continues down through the tube, is reflected from the mercury surface, and comes to a focus on a small photographic plate located just under the lens.

The instrument is arranged so that the lens and plate may be tilted as a unit through a small angle without appreciably

altering the position of the image on the plate. Each zenith star is photographed twice, with the plate and lens rotated through 180 degrees between exposures. Meanwhile the instrument is driven from east to west to keep up with the star, and the clock time and plate positions are automatically recorded. Since the distance on the plate between the images photographed before and after reversal corresponds to twice the zenith distance of the star, it is possible to deduce the times of transit by measurement, and from these data determine the clock time within a thousandth of a second.

The Naval Observatory at present is the only observatory in the world using this simple and highly accurate automatic method of obtaining time. It is also the only observatory which broadcasts the time automatically at regular intervals; once each hour. The photographic zenith tube was originally designed by F. E. Ross for the determination of variation of latitude, and adapted to its present work by F. B. Littell and J. E. Willis. The sidereal clocks used in the time determination are maintained under constant temperature and air pressure, are never disturbed, never reset, never interfered with in any manner except for repairs. So regular are they, it is possible to predict their daily variation from star time within a few thousandths of a second.

The observatory's telescopic equipment has recently been augmented by two new instruments, both unique in their respective fields. One is a 15-inch photographic refractor by Warner & Swasey, equatorially mounted and equipped with two auxiliary telescopes to be used in guiding the instrument.

The other, a 40-inch reflector (Plate 22), is the only representative in this country of the Ritchey-Chrétien type of photographic reflecting telescope, devised jointly by the American telescope-maker George W. Ritchey, and Henri Chrétien, a French optician. The curves of the mirrors (it is a Cassegrain) are not respectively paraboloidal and hyperboloidal, but are specially figured to take in a larger portion of the sky than such mirrors can bring to focus.

Designed for photography, it is provided with an especially

Keystone Views

DIPPING GLASS OUT OF THE MELTING TANK DURING THE POURING OF THE FIRST DISC FOR THE 200-INCH TELESCOPE

THE FIRST 200-INCH DISC AS IT APPEARED WHEN REMOVED FROM THE ANNEALING OVEN

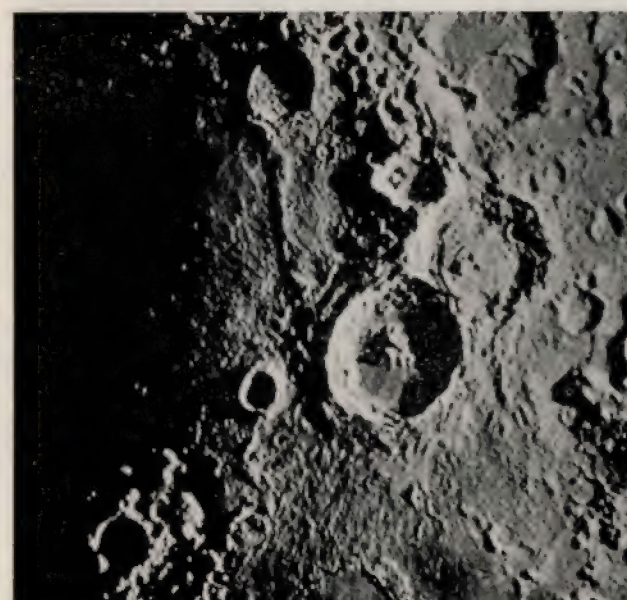
[PLATE 17]

Yerkes Observatory

THE GREAT NEBULA IN ANDROMEDA: AN EXAMPLE OF FINE DEFINITION IN ASTRONOMICAL PHOTOGRAPHY
Taken by Professor George W. Ritchey on the 24-inch reflector at Yerkes Observatory

[PLATE 18]

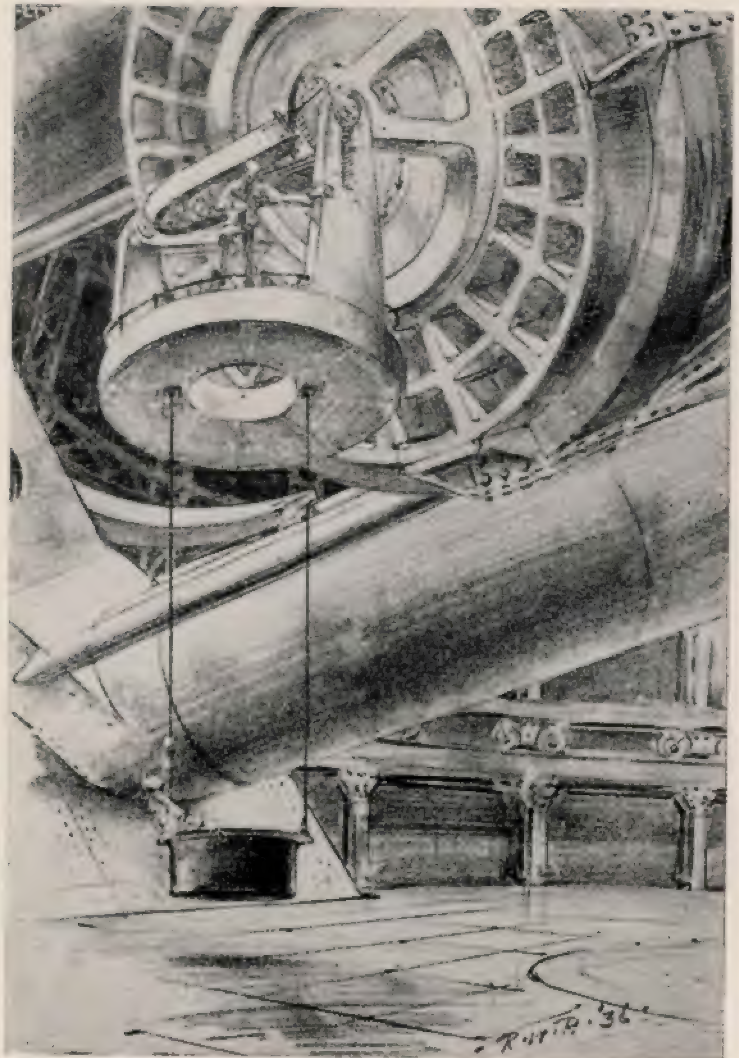
Mt. Wilson Observatory



Yerkes Observatory

PORTIONS OF THE MOON AS SEEN THROUGH DIFFERENT MODERN INSTRUMENTS
The 100-inch Mt. Wilson reflector (above) and the 40-inch Yerkes refractor

[PLATE 19]



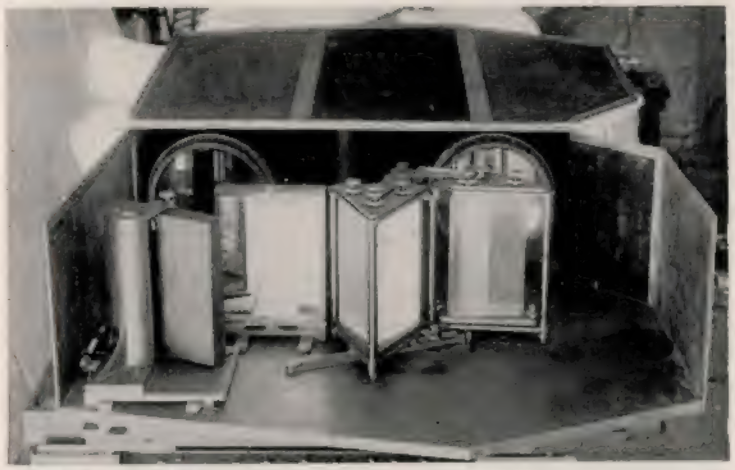
Drawing by Russell W. Porter

HOW THE SPECTROSCOPE WILL APPEAR AT THE CASSEGRAIN FOCUS OF THE 200-INCH TELESCOPE
Also the elevator by which the astronomers will reach it. Note cellular structure of the back of the mirror, and the huge pivoted platform for observers

[PLATE 20]

Mt. Wilson Observatory

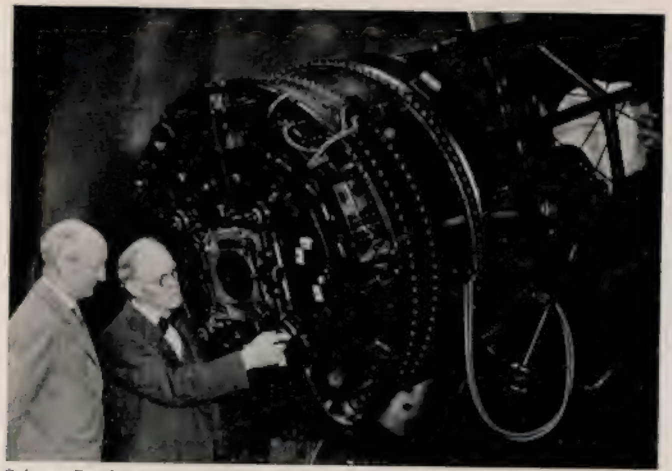
Dr. Albert E. Whitford



Mt. Wilson Observatory

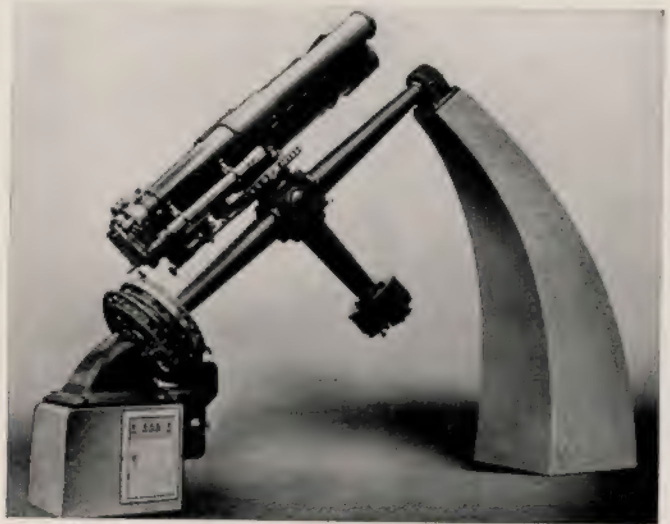
ASTRONOMICAL AUXILIARIES
A thermocouple (upper left) for measuring planetary and stellar radiation; photo-electric photometer and thermionic amplifier (upper right), and the optical train of a spectroheliograph

[PLATE 21]



Science Service

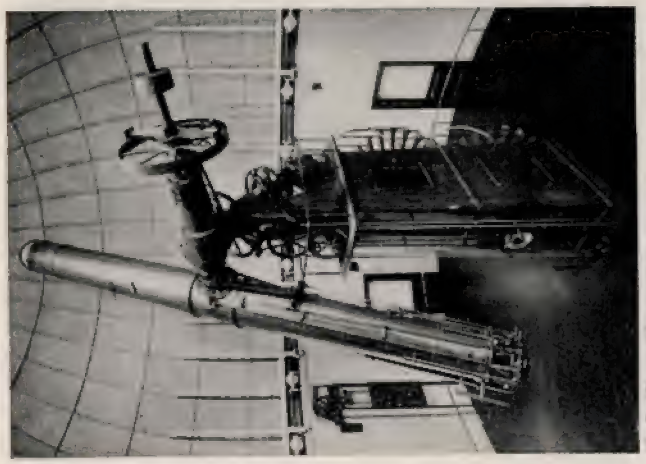
PROF. GEORGE W. RITCHEY ADJUSTS THE NEW RITCHEY-CHRETIEN REFLECTOR WHILE CAPTAIN FREDERICK HELLWEG, DIRECTOR OF THE U. S. NAVAL OBSERVATORY, LOOKS ON

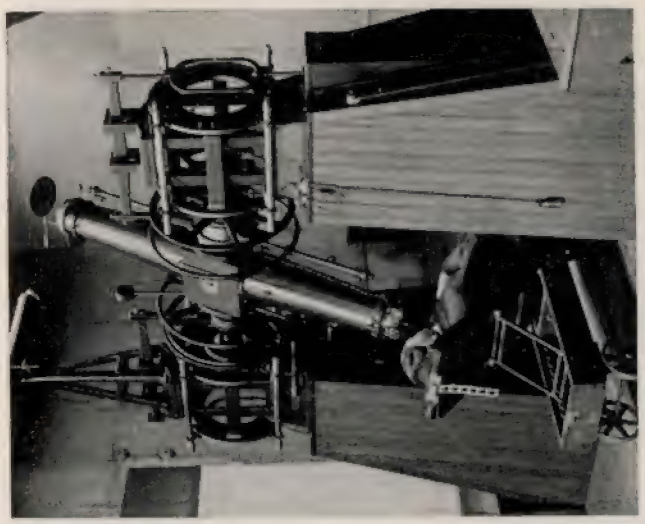


Warner & Swasey

THE NEW 15-INCH PHOTOGRAPHIC REFRACTOR OF THE U. S. NAVAL OBSERVATORY

[PLATE 22]

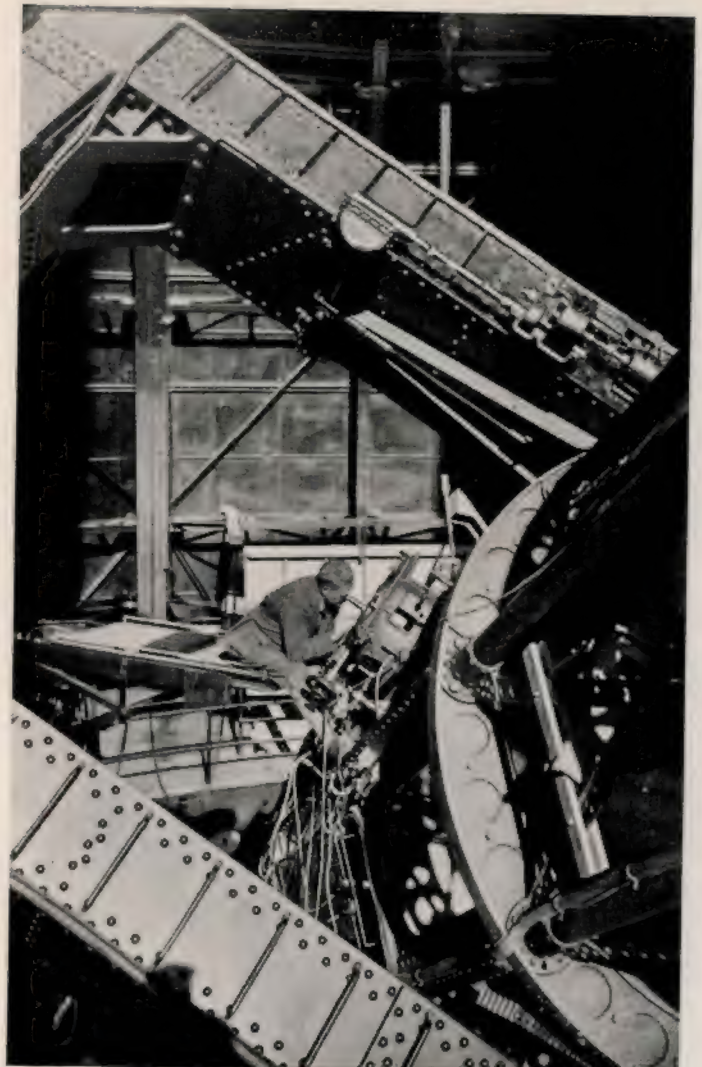




U. S. Naval Observatory

HISTORIC CLARK REFRACTOR OF U. S. NAVAL OBSERVATORY (LEFT) AND 6-INCH TRANSIT WITH ASTRONOMER IN OBSERVING POSITION

[PLATE 23]



Mt. Wilson Observatory

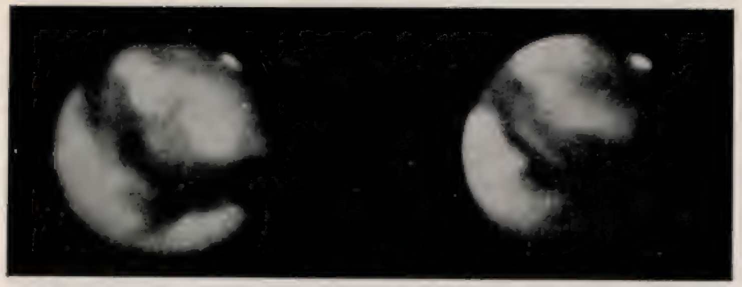
OBSERVER AT CASSEGRAIN FOCUS OF 100-INCH TELESCOPE

[PLATE 24]

Lick Observatory

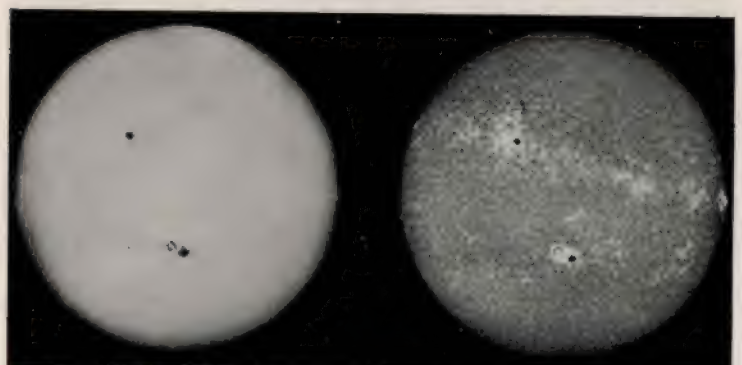
A SPECTROGRAPH IN PLACE AT THE EYE-END OF THE 36-INCH LICK REFRACTOR

[PLATE 25]



TWO VIEWS OF MARS TAKEN A MONTH APART. NOTE CHANGES IN SURFACE MARKINGS

JUPITER PHOTOGRAPHED BY ULTRA-VIOLET LIGHT (LEFT) AND BY ORDINARY BLUE-VIOLET LIGHT



All photos Mt. Wilson Observatory

THE SUN, PHOTOGRAPHED IN WHITE LIGHT (LEFT) AND IN CALCIUM LIGHT

[PLATE 26]

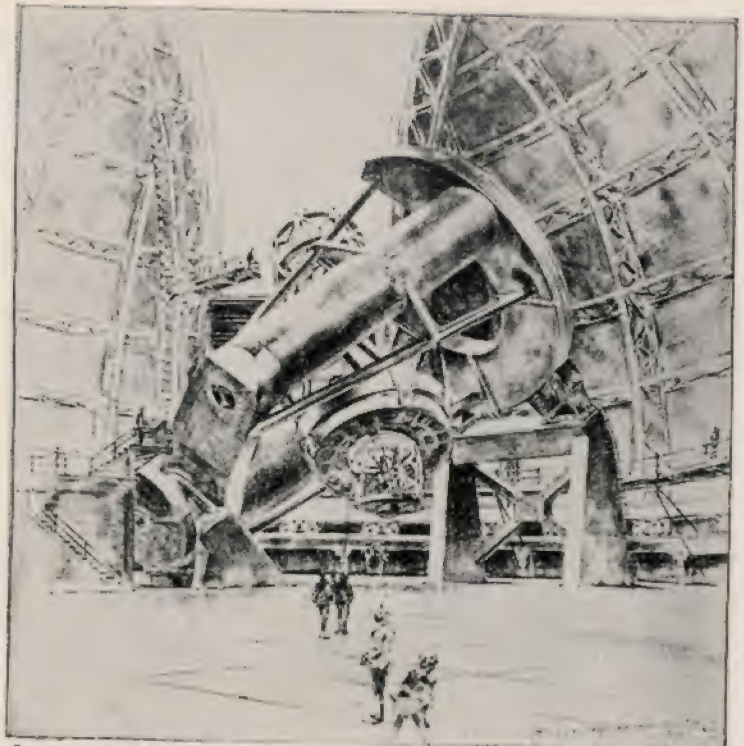
Mt. Wilson Observatory

THE 60-FOOT TOWER TELESCOPE AT MT. WILSON OBSERVATORY

[PLATE 27]

The 24-26-inch Schmidt-type telescope at the Warner & Swasey Observatory.
(PLATE 28)

The Harvard College Observatory coronagraph at the Fremont Pass station, Climax, Colorado.
(PLATE 29)



Drawing by Russell W. Porter

THE WORLD'S LARGEST "EYE" LOOKS QUESTIONINGLY INTO THE SKY

Mr. Porter's conception of the appearance of the completed 200-inch telescope in its dome atop Mt. Palomar

[PLATE 30]

Drawing by Russell W. Porter

THE OBSERVERS CHANGE WATCH AT THE PRIME FOCUS OF THE 200-INCH TELESCOPE

[PLATE 31]

short tube which does not interfere with the wide field. In order to protect the exquisite figure of the mirrors, provision has been made to keep them at a constant temperature; it is the world's first air-conditioned telescope.

This feature is carried out not only in the construction of the instrument, but also in the building in which it is housed. It is a new structure made of light metal with double walls. The metal does not store up heat as does heavy stone or brick construction, and after nightfall radiates it away rapidly, whereas with other types of buildings the air ripples caused by the slow loss of heat sometimes produce flickering images and bad seeing all night long.

The refinements of this telescope are carried even to the shape of the photographic plates used with it. Instead of the ordinary flat kind, they are curved, each being given an optically correct surface in order to provide still greater freedom from distortion. The correctly curved surface is obtained, not by figuring the glass, as originally planned, but by a much less expensive method suggested by Commodore Hellweg. The plates are gently drawn into the desired figure by suction applied from beneath, the curvature being regulated by a bronze matrix which holds the plate during exposure. When the suction is released, the plate resumes its ordinary flat form without distortion of the image. By this means sharp Ritchey-Chrétien photographs are obtained on standard plates.

VI

From about 1850 until near the close of the century there began to appear in this country a strange phenomenon, the "stock company" observatory. People in all parts of the country began contributing funds to build local observatories much as nowadays they contribute to the building of golf clubs.

What brought about a movement of this sort is hard to say. Perhaps it was a delayed manifestation of the great surge of interest in astronomy which began in England in the time of William Herschel, an enthusiasm for which we have had no

modern counterpart. It is hard to imagine official Washington, for instance, turning out to honor with national festivals the discoverer of a new planet. It is difficult to picture a King of England in our time leading an archbishop through the tube of a reflecting telescope with the remark, "My lord bishop, I will show you the way to heaven," or conceive of crowds gathering to see an astronomer pass along the street. Yet such things happened in the time of William Herschel.

Nor did the popularity of astronomy come to an end with this astronomer's death in 1822. John Herschel, his son, was an even greater idol. His grace, manners, handsome appearance, and the glamor of his life caught public fancy, and the whole world followed his discoveries. When John Herschel made his famous journey to South Africa (1834-1838) to view the sub-equatorial heavens, his every announcement was received with enthusiasm and acclaim. His exploits were played up by the newspapers of two continents, the true ones with the false. On one occasion a hoax, in which he was supposed to have discovered the inhabitants of the moon, gained such currency that some of it even crept into technical literature. Newspapers published the story as fact, even after it had been proved untrue. People were eager to believe such things then, as now; and never before had a man appeared who seemed so wonderfully able to bring marvels to pass as John Herschel.

Also, in the middle of the century, there was Lord Rosse's magnificent 6-foot telescope to stir speculation and interest; not to mention the important, exciting, and widely discussed new theories of celestial mechanics—of the shape of the galaxy, of the origin of stars and planets, of the relation to our galaxy of the "island universes"; questions raised and partly answered by a series of famous and important men, among them Immanuel Kant, Pierre Simon Laplace and Carl Friedrich Gauss.

Associated with all this was the strong religious sentiment of the time, which contemplated the wonders of the firmament as marvels from the hand of God. It was a religious attitude, be it noted, exactly the reverse of that in the day of Copernicus, Bruno and Galileo. The hardy Protestants of eastern and middle-western America considered study of the skies akin to godliness, and were eager themselves to look upon the authentic handiwork of so magnificent a Creator.

One of the first of the observatory stock companies was organized at Cincinnati, in 1842. The project went over well; a refracting telescope 11 inches in diameter was purchased. The Litchfield Observatory of Hamilton College was similarly founded by public subscription in 1856, and endowed by Edwin C. Litchfield, of Brooklyn, N. Y. At about the same time the observatory of the University of Missouri was founded by public contributions, and in 1856 Dudley Observatory, at Albany, N. Y., began its long career of useful work on funds supplied as gifts from citizens of the city, its name being taken from that of the largest donor.

In 1862 the Dearborn Observatory of Northwestern University, at Evanston, Ill., came into existence through the large gift of a benefactor whose name became that of the institution; but the instruments set up in it were paid for in large part by popular subscription. In various other cities and towns similar observatories appeared. Many of them did not long survive, for once the novelty has worn off there is little fun to be had in looking through a telescope unless a directing head is present to explain and give meaning to what is seen. A number of the little observatories of the 1800's had no such directors, could not afford to pay salaries, and one by one succumbed to time and circumstance.

There were notable exceptions, however; one of them we shall now consider.

VII

Over at Pittsburgh, city of industry, steel, electricity and coal, a meeting is in progress. It is the evening of February 15, 1859, and a number of citizens of Allegheny and Pittsburgh have gathered, not to discuss markets, manufacturing methods or labor conditions, but to form the "Allegheny Telescope Association." Their purpose is to arrange for the purchase of a telescope—a real telescope, "the magnifying power of which

will bring the heavenly bodies near enough to be viewed with greater interest and satisfaction."

There is much discussion of ways and means. Money is to be raised by subscription, and though everybody present is very much interested in the stars, some are for buying only a small instrument, such as might give a glimpse of the craters of the moon, or the satellites of Jupiter. But up rises a man from the crowd, addressing the Chair:

"Mr. Chairman," he says, "the country contains many small observatories. Crippled by instruments too weak for any real use, they have quickly lost the support of the public. Since astronomers can do nothing with them, they have gone bankrupt and disappeared. Now, I propose that Allegheny Observatory start life with a real instrument; the best we can buy—an instrument that can make astronomical discoveries as well as delight the members of this association."

Who gave this counsel is not known, for the records of that first meeting are meager. But a few weeks later the new observatory purchased a 13-inch refracting telescope from Fitz, of New York, who only a short time before had sold a similar instrument to the Dudley Observatory. The Allegheny telescope was tested by Dr. Lewis Rutherfurd, of New York, and Dr. Franz F. E. Brünnow, first director of the University of Michigan Observatory. It was found satisfactory, and the instrument was installed in its new building in January, 1861.

More than two years elapsed before there was a regular director. The heads of the observatory were looking around for the right man: a man of zeal and attainments who would take charge for the salary they could afford to pay. Finally they found him, in the person of Professor Philotus Dean, who became director in 1863. Professor Dean was undoubtedly a man of zeal, and as for pay, he was willing to work for no salary at all except a dwelling house free of rent. He was what may be called an eccentric; he entertained the highly disconcerting notion that the telescope was to be preserved at all costs—but not used. When amateur stargazers came to take a look at the skies they were met at the door by Professor Dean flourishing a

shotgun. It followed that by 1867 the members of the association were utterly weary of their observatory. In that year they made a free gift of it to the Western University of Pennsylvania—now the University of Pittsburgh.

It was in the person of its second director that Allegheny Observatory found a man who knew how to turn its instruments to their proper use. He was none other than Samuel Pierpont Langley, later to become secretary of the Smithsonian Institution at Washington. It was Langley who put solar observation on a firm basis in this country, invented the bolometer, measured the heat of the sun's "dark rays," made great progress in the study of aerodynamics, and all but became the first man to fly in a heavier-than-air-machine.

Langley used to say, as the belching chimneys of growing Pittsburgh darkened the observatory's sky, that this was no obstacle at all to the kind of work he was carrying on. In fact, said Langley, the smoke-filled sky was ideal for studies of the sun; it cut off the worst of the glare, and made the seeing steadier!

At the very beginning of Langley's service as director, the object-glass of the 13-inch telescope was stolen by a ransom-demanding thief who placed high value on it. This was really a sequel to the eccentricities of the observatory's first director, who, with the aid of his shotgun, succeeded in giving the citizenry of Pittsburgh such an exaggerated notion of the value of the instrument it is little wonder an attempt was made upon it.

Langley's method of dealing with the matter was firm. He argued that not a cent should be paid unless the thief could be punished; otherwise no large lens in the country would be safe. One evening he met the thief by appointment. As they walked up and down a wooded path the lens-kidnaper remarked: "You are a gentleman, and I am a gentleman; we must trust one another." Said Langley, "No gentleman steals a telescope." The object-glass was finally returned uninjured, and without the payment of ransom.

When Langley left to take up his new duties in Washington,

he was followed in the directorship by James Edward Keeler, later to become director of Lick Observatory. It was Keeler who first produced spectroscopic proof that the famous rings of Saturn are not solid, but consist of swarms of satellites, like encircling clouds of brickbats. To such an exploit he added photographic and spectrographic work of the most fundamental kind, and had he lived longer Keeler probably would have been one of the best-known men in American astronomy.

Following Keeler as director of Allegheny Observatory was F. L. O. Wadsworth; then Dr. Frank Schlesinger, later director of Yale University Observatory. He was succeeded by Dr. Heber D. Curtis, who subsequently became director of the University of Michigan Observatory.

The present acting director of Allegheny is Dr. Nicholas E. Wagman, specialist in stellar parallax, adding still another to the list of noted men who have been connected with this observatory. The American telescope-maker John A. Brashear began his career in connection with Allegheny, and made its fine modern equipment, which includes a 30-inch photographic refractor, one of the best in existence, and a 30-inch Cassegrain reflector, known as the Keeler Memorial Telescope. In a crypt in the base of this telescope are the ashes of Keeler, brought back from California, and those of Brashear and his wife, Phoebe.

The present work of Allegheny Observatory includes the determination of star parallaxes (in which this observatory for years has led the world), the measurement of magnitudes by the photographic method introduced by Dr. Frank C. Jordan, former director, and the photographic observation of double stars with the great refractor, by Dr. Keivin Burns.

VIII

In the matter of stellar parallaxes Allegheny is rivaled in North America only by Leander McCormick Observatory of the University of Virginia, located at Charlottesville.

Leander McCormick is not an old observatory, as go most

of the institutions we have been discussing; it was founded in 1883 by the son of the inventor of the reaper. Since that time 1350 parallaxes—star distances—have been obtained there, together with the proper motions by photography of 18,000 faint stars.

The major instrument of this observatory is a 26-inch refractor made by Alvan Clark, the companion instrument of the great refractor at the United States Naval Observatory with which Dr. Hall discovered the satellites of Mars.

Leander McCormick, like Allegheny, has enjoyed association with the names of many great astronomers. Its first director was Dr. Ormond Stone, brother of the Melville Stone who between 1898 and 1921 served as general manager of the Associated Press. The present director is Dr. Harold L. Alden, formerly astronomer in charge of the Yale Observatory station in South Africa.

Other well-known men who have worked there are Dr. Edgar Odell Lovett, president of Rice Institute; Dr. H. Y. Benedict, president of the University of Texas; Dr. Herbert R. Morgan, astronomer of the United States Naval Observatory; the late Dr. Heber D. Curtis, director of the University of Michigan Observatory; Dr. C. P. Olivier, director of the Flower Observatory of the University of Pennsylvania and Dr. S. A. Mitchell, director emeritus.

IX

We must now consider the story of still another American observatory; this one uniquely founded to test a theory which many persons consider a fallacy.

For when the Italian astronomer Giovanni Schiaparelli began his systematic study of the planet Mars at the Royal Observatory of Milan about 1877, he set in motion a chain of events culminating in the foundation of the Lowell Observatory at Flagstaff, Arizona; an observatory that has since given the world a wealth of knowledge about the planets, provided the solar system with a ninth known member of the planetary sister-

hood, and, plunging farther into space, laid bare the colossal radial velocities and rotations of the nebulae.

Schiaparelli's study led to the challenging discovery that the surface of Mars, the planet next to the earth in the direction outward from the sun, is figured with a series of puzzling markings having the appearance of artificial origin. These marks the Italian called *canali,* because he thought them rivers or channels connecting larger bodies of water—the large dark areas.

The theory, first advanced by Percival Lowell and later embraced by Schiaparelli, was that the markings are indeed the work of intelligent beings somewhat like ourselves, and represent the efforts of a hard-pressed race of Martians to meet the drying of their planet by providing vast conduits to bring water from the polar ice-caps. If this be true, the *canali* are of course not the canals, which could not under any circumstances be seen at such a distance, but the broad lines of vegetation extending on either side of the conduits. The Nile Valley, seen from the distance of Mars, might perhaps present a similar appearance. It would be practically invisible in the winter months, but in the growing season would stand out against the surrounding sands as a broad line of green.

Schiaparelli's discovery of the "canals," and Lowell's theory explaining them, fired the world with interest in our planetary neighbor, inspired dramatic stories such as *The War of the Worlds,* by H. G. Wells, and caused many a telescope which had formerly been engaged in the study of stars to turn with curiosity and wonder toward our nearer neighbor. But most important of all, it moved Lowell himself to forsake business, literature and diplomacy, and to devote his fortune and the remainder of his life to a systematic study of the planet, primarily to continue the investigations of Schiaparelli, whose eyesight had begun to fail in the early '90s, and whose days of observing were coming to an end.

Percival Lowell was a man of remarkable variety and talent. Graduated from Harvard *cum laude* with honors in mathematics, he had turned his hand to diplomacy and literature with skill and success, and had finally returned to Boston to

make himself well-to-do in business, serving variously as a cotton-mill executive and a director of trust and electric companies.

Lowell began his astronomical adventure sensibly, with a methodical search for the best possible place to establish a planetary observatory. Observation of the planets presents problems somewhat different from those confronting the observer of stars or nebulae. For one thing, magnification assumes a relatively larger place; here are objects resolvable into definite discs, upon which details may be discerned. But magnification is useless without sharp, steady images, filled with detail and bright enough for rapid photography or spectographic study.

Lowell visited France, Algiers and many possible sites in North America. An expedition was organized to observe from the high plateau near Mexico City; another was sent to the Andes. At length the present site in Arizona was selected. It is near the San Francisco Peaks, about a mile west of the town of Flagstaff. The observatory grounds, comprising about 700 acres, lie on the eastern edge of a volcanic mesa 350 feet above the town and 7,250 feet above sea level.

The decision to locate at Flagstaff was made in the winter of 1893-94. The search had consumed considerable time, and Lowell was eager to begin his work when Mars was at opposition, or closest to the earth, in 1894. Thanks to happy circumstance, there chanced to be available an 18-inch refracting telescope in the hands of its makers, the John A. Brashear Company. This instrument, now at the Flower Observatory of the University of Pennsylvania, was obtained as a loan. Observation of Mars began at Flagstaff in May, 1894.

Meanwhile, a larger telescope of the highest possible perfection was ordered from Alvan Clark & Sons. Good fortune accompanied the construction of the new refractor, for it was completed in a remarkably short time, and was in use in the autumn of 1896. This instrument has a clear aperture of 24 inches and a focal length of 386 inches. In 1901 it was fitted with a correcting lens for photography. By means of color filters and properly sensitized plates the planets are regularly photo-

graphed with it by ultra-violet, blue, yellow, red and infra-red light.

In 1909 a 42-inch reflecting telescope was installed to complement the work of the refractor. It, too, was made by Alvan Clark & Sons, and mounted on a rectangular polar axis. It is fitted with several secondary mirrors which permit variation of the focal length from about 18 feet up to 150 feet. With this instrument Dr. William W. Coblentz, of the Bureau of Standards, did his radiometric work with the improved thermocouple in 1921, establishing the methods by which he and Dr. C. O. Lampland have since measured the temperatures of the planets.

In 1915, Lowell predicted that a ninth major planet would some day be found, far out at the edge of the solar system in an orbit beyond Neptune. He reached this conclusion from a study of the deviations of Uranus, wabbles in its orbit which the astronomer believed could be caused only by the influence of an unknown outer body. He did not live to see the fulfilment of his prophecy, for he died suddenly at Flagstaff in 1916. But the search for the trans-Neptunian planet which he inaugurated, and which was continued by Dr. V. M. Slipher, present director of the observatory, bore fruit dramatically on February 18, 1930. On that date the planet afterward named Pluto was picked up photographically at Lowell Observatory by the young astronomer, Clyde Tombaugh, within a few degrees of the place where Lowell predicted it would be. The discovery was made with the aid of a refracting telescope specially designed for the planet search, a photographic instrument of 13-inches aperture, completed in 1929 after much searching with poorly suited instruments.

Lowell's theories of the inhabitants of Mars were opposed, sometimes bitterly, during his lifetime. Observations since have confirmed his conclusions that the planet has a very appreciable atmosphere and that the temperature rises much above freezing. Lowell Observatory studies have shown considerable air on Mars—clouds have been observed fifteen miles above its surface —but there is very little water, and probably great extremes of heat and cold. Such conditions perhaps preclude the existence

there of human beings. Many of the other life forms present on earth must also be ruled out; yet there are seasonal changes which clearly indicate vegetation. Who shall say that the human form is the only one in which intelligence, scientific skill and capacity for great engineering achievement can abide?

Planetary research of the type carried on at Lowell Observatory is the most absorbing in astronomy. One returns with relief from contemplation of stars and galaxies to consider whether there is not some living link, some bond of intelligent sympathy, between the earth and its planetary neighbor. However, studies at Lowell have not by any means been limited to the investigation of Mars and the other planets. The first good spectrograms ever made of the spiral nebulae were taken there by Dr. V. M. Slipher, made with a spectrograph designed with great skill by the astronomer himself. This instrument, by employing a short focus camera and a relatively wide slit and powerful prism, greatly reduced the exposure time and made the observations possible. Dr. Slipher discovered the enormous radial velocities of the nebulae and star clusters as a result of this work, information on which the much-discussed theories of the "exploding universe" have been based.

Another major task undertaken at Lowell was the investigation of the spectra of the major planets, which revealed a remarkable series of atmospheric absorption bands, particularly in Uranus and Neptune. Dr. Silpher and Dr. Arthur Adel, of the observatory staff, were able in 1934 to identify almost all of these bands as due to methane—a few to ammonia. They thus determined that the "air" of those planetary giants is composed principally of marsh gas—which does not, of course, prove the presence of organic material. Methane may be produced in various ways besides the decomposition of vegetable matter.

Chapter XIV

TODAY'S EYES OF THE EARTH—THE GIANT OBSERVATORIES AND THEIR TELESCOPES

I

OF the 300 or so observatories now active in the world, more than eighty are located in the United States and Canada. On this continent are to be found the largest and most active telescopes, and, with few exceptions, the most famous observatories on earth.

To some extent the amazing prosperity of our country in the last 100 years has made this possible, for large telescopes are luxuries; no other country has been able—or willing—to raise such huge sums for eyes to look at the stars. But it would be unfair to attribute the growth of great American observatories to prosperity alone. America has produced or attracted many of the world's greatest scientists; astronomy has progressed faster here than anywhere else, and this was true even before our observatories were bigger and better equipped than those of Europe. The story of America's giant observatories is really the story of unusual men—men whose vision prompted them to give generously for this cause, and men who knew how to make good use of the fine modern instruments these gifts brought into being.

The Brobdingnagian observatories which we shall now consider are today's giants in the earth, the unique flowering of our astronomical and mechanical age, perhaps the greatest that will ever be seen on the globe. They include Lick, Yerkes and Mt. Wilson; the Dominion Astrophysical Observatory; Canada's newest, the David Dunlap Observatory of the University of Toronto, and several others.

The earliest of them was Lick Observatory, an institution which is certainly no less valuable to science because, as has often been said, it is a monument to the curious fancy of an eccentric California millionaire. James Lick was no ordinary eccentric: crotchety in small things, mean in big ones; his was the grand manner. When he decided that there should be an observatory bearing his name upon a mountaintop of his state, he specified that it should be no ordinary little place for gazing at the stars. It was to be a very giant among observatories, containing a telescope "superior and more powerful than any telescope yet made." And to this end he provided $700,000 for the construction of buildings, the purchase of land and the making of the telescope, "with all the machinery appertaining thereto."

Mr. Lick himself selected Mt. Hamilton, in Santa Clara County, a few years before his death in 1876. The firm of Alvan Clark & Sons made the lenses for the "powerful telescope"—a refractor of 36 inches aperture; Warner & Swasey mounted it. It stands today under the great white dome of the observatory, the second largest refracting telescope in the world, and in its base the body of James Lick is buried. The observing room has a rising floor, a novelty since copied extensively elsewhere. It provides a convenient means of reaching the eyepiece of the instrument at any angle; the floor being lowered for observing near the zenith, and raised for observations near the horizon.

The graceful refractor is a masterpiece of design, both as to lenses and mounting. It was originally made for visual use (in 1876 a large telescope of any other kind would have been useless), but it now has a correcting lens of 33-inch aperture which converts it into a photographic telescope. This is done by placing the correcting lens in front of the regular objective.

The magnification of the instrument can be increased from about 270 to more than 3,000 diameters with the use of different eyepieces. The power actually employed depends of course on the object under observation and the quality of the seeing. However, powers greater than 1,000 are seldom useful.

The refractor is the chief instrument of the observatory, but

it has as companions some other very notable telescopes, including the famous Crossley Reflector, a 36-inch presented to Lick in 1895 by Edward Crossley of Halifax, England. The mirror of this instrument was made by Sir Howard Grubb, later one of the founders (with Sir Charles Parsons, son of Lord Rosse) of the British telescope firm of Sir Howard Grubb, Parsons & Company. It was one of the first mirrors experimentally coated with aluminum instead of silver, by the Strong process.

When Mr. Lick endowed his observatory he apparently was chiefly interested in its giant instrument. But the first director, Dr. Edward S. Holden, was interested also in results. He selected a notable staff of astronomers and laid out a program of work on radial velocities and proper motions of stars which very soon made Lick Observatory a leader in that field. Among the directors and staff members of Lick through the years have been some of the world's foremost astronomers: James Edward Keeler, S. W. Burnham, E. E. Barnard, W. J. Hussey, Robert Grant Aitken, William Hammond Wright, Charles Donald Shane, and others. Dr. C. D. Perrine, now director of the Argentine National Observatory, was formerly a member of the staff at Lick. So was the late Dr. Heber D. Curtis, director of the University of Michigan Observatory. Lick Observatory's influence on astronomy goes far beyond any estimates based on men or discoveries alone; it was a new kind of institution, and a new force. It helped mold the thinking of astronomers throughout the world. It had an important bearing on the decision of Dr. George Ellery Hale, a young man in his teens when he first visited it, to take up astronomy. It thus served as a sort of mentor and inspiration to the man who created three of the subsequent giant observatories of North America.

Even in that time astronomers had begun saying that the day of dramatic "discoveries" in astronomy had gone; hereafter the work of observatories would be humdrum and prosaic —the laying out of large programs or surveys of the skies, such as the determination of radial velocities, parallaxes, or the spectral types of stars. In a measure they were right. Astronomy

had grown up. But nevertheless, "discoveries" too began to be made at Lick.

In September, 1892, the 36-inch refractor revealed the very faint fifth satellite of Jupiter, a body only about 100 miles in diameter and very much closer to the planet than any of the four bright satellites known since Galileo's time. Subsequently, in 1904, 1905 and 1914, three additional satellites of Jupiter were found photographically with the Crossley Reflector, two of them too faint to be detected by the eye in the most powerful telescope then available. Twenty-nine comets were also discovered.

Presently, as though not content with its northern conquests of the sky, Lick reached out from its perch atop three-humped Mt. Hamilton and sent an exploratory tentacle into the south, one of the first of the great Northern observatories to do so. Until 1929 it maintained, through the generosity of various donors, a southern station on the summit of Cerro San Cristóbal, near Santiago, Chile, to carry out in the southern hemisphere the important program of study of the radial (line of sight) velocity of stars which had been started by Lick Observatory in the north in 1896. The establishment of this station was made possible in 1903 by the late D. O. Mills, grandfather of Ogden L. Mills, former Secretary of the United States Treasury.

The result of this program in both hemispheres was the determination of radial velocities of more than 3,000 of the brighter stars. It also revealed the "proper motion" of the sun, showing that with respect to the brighter stars it is traveling through space at a velocity of about 12½ miles a second, in a direction toward the dividing line between the constellations Hercules and Lyra.

II

While these things were taking place in the West, events were also moving in the continent's middle regions. James Lick had been sleeping the last long sleep only sixteen years in his monumental tomb when by the stroke of a pen it ceased to be

the foundation of the greatest telescope in the world. Another was being built—and by the hands of the same makers, for a new observatory at Williams Bay, Wisconsin.

This was Yerkes Observatory of the University of Chicago, established in 1892 through the gift of Charles T. Yerkes, a Chicago business man. But the inspiration for it came from that imaginative astronomer and observatory-organizer, that most unusual of gifted men, Dr. George Ellery Hale.

Dr. Hale was then only twenty-four years old, yet he was already associate professor of astrophysics at the University of Chicago, and had put behind him what might have been counted an ordinary lifetime of achievement in astronomy. From the time he turned sixteen he had been an astronomer, had built with his own hands some of the instruments in his notable Kenwood Observatory, and after a spectacular series of experiments perfected, only three years before the founding of Yerkes, one of the most precious instruments in the armamentum of the modern sun-explorer—the *spectroheliograph.* When he made this epochal invention he was twenty-one. Any astronomer in the world would have traded a lifetime of scientific triumph to have made that one simple, fundamental invention in his place.

But even then Hale was going on to greater things. More telescopes and better observatories were the need of his new science of astrophysics, and he had undertaken to get them.

One evening he heard Alvan Clark, by then the country's foremost telescope-maker, tell an unusual story. It seems that when Lick Observatory installed its 36-inch refractor in 1876, the fame of the huge instrument spurred a group of boosters in Southern California to try to rival or exceed it. Raising a little money, they promptly commissioned Clark to make a larger instrument, to be located at Los Angeles. Clark obtained the glass—two 40-inch discs, and began working on the lenses. But before they could be finished the Los Angeles boom of the moment broke with a sickening slump in real estate. Promptly the syndicate of Los Angeles telescope enthusiasts went bankrupt. The bill—$16,000—remained unpaid.

Alvan Clark, used by this time to the tricky reversals of the world's trickiest business, told the story with a wry smile—a good joke on himself. But growing serious, he exclaimed, "Just the same, some millionaire should be found who would complete that beautiful telescope!"

Out of the group that sat listening, only one man glimpsed the possibilities Clark had revealed. The story goes that Hale went the same evening to Dr. W. R. Harper, president of the University of Chicago, and together they visited the home of Charles T. Yerkes, whom Hale knew slightly. They laid before that careful business man such an ardent dream that Yerkes was entranced. He agreed at once to study the proposition of building the world's greatest observatory for the University of Chicago. A few days later Hale telegraphed Clark to go ahead on the 40-inch objective. He had made a powerful convert to astronomy, had launched himself on a new phase of his spectacular career—and incidentally, before he had yet experienced a quarter-century of life, found himself director of an institution which has been reflecting glory upon his foresight, the generosity of its donor, and the University of Chicago ever since.

The mechanical parts of the great telescope, made by Warner & Swasey, were completed in 1893, and were exhibited that year at the Columbian Exposition in Chicago. The lens, a full 40 inches in diameter, was completed in October, 1895. It was then—and still is—larger by four inches than any other successful refracting telescope in the world. It is probably the largest refractor that will ever be made.

The objective consists of two pieces of glass, of which the front, or crown, is about 2½ inches thick at the center, and tapers off toward the edges. The second lens, made of flint glass, is about 8 inches farther down the tube of the telescope and is 2 inches thick. The lenses were made as thin as possible in order to reduce the absorption of light within the glass. They were figured in such a way as to bring the light to a focus at 62 feet.

The light-gathering power of the 40-inch objective is more

than 35,000 times greater than that of the unaided eye; hence the usefulness of this telescope in giving bright, well defined images. It is possible, theoretically, to obtain a magnification of 4,000 diameters, but as in the case of the 36-inch refractor and most other telescopes, powers greater than 1,000 are seldom used. The resolving power of the instrument is such that the angle between two stars separated by so small an interval as a tenth of a second of arc can be measured with a micrometer. When it comes to photography the refractor does even better. Displacement can be measured on photographs taken with the 40-inch which correspond to 1/100 of a second of arc, or about the apparent diameter of a quarter-dollar viewed at a distance of 300 miles.

The mounting resembles that of the 36-inch Lick telescope. It stands on a massive brick pier, which in turn rests on a solid concrete foundation. The upper part of the mounting consists of a column of cast-iron in four sections, the top chamber of which houses the driving clock. The center of motion of the telescope is 61 feet above the ground. The instrument itself is 63 feet in length; the moving parts, including the telescope, the declination axis and the counterweight, weigh twenty-tons, yet so finely is it mounted, and so exquisite the balance, that it can easily be moved from one position to another by hand. In astronomical work electric motors, of which there are half a dozen or more, move the instrument quickly to new locations and work the slow motions. With the latter the telescope can be centered exactly upon an object with a movement at the eyepiece of less than 1/100th of an inch at a time.

To bring the telescope to bear on an object, the operator moves it approximately to the proper spot by gauging the correct right ascension and declination on large graduated circles. He then locates the object through a small finder of three inches aperture, and having centered it on the cross-wires, refines the adjustment by looking through a second finder of four inches aperture. For the finest adjustment, there is still a third auxiliary—a six-inch guiding telescope of the same focal length as the large instrument. The motions necessary to bring the heavy

instrument into exact bearing on the object are all controlled electrically, and respond to slight pressure of the operator's fingers. The floor of the observing room rises automatically to accommodate itself to the telescope; the eyepiece is always within convenient reach.

The 40-inch telescope is used for observing the stars on every clear night and the sun on all clear days. It is a truly famous instrument; besides the great number of stellar and planetary photographs made with it, the huge refractor has aided in innumerable forward-looking experiments. One of the earliest applications of the interferometer to astronomy was made by Professor Albert Michelson, then of the University of Chicago, with this telescope. A new type of instrument, working on the principle of the interferometer and used with the refractor, was later made by Professor George Van Biesbroeck, of the observatory staff, and is now used for the observation of double stars. The bright star Capella, known as a spectroscopic binary but never resolved in any telescope, has been seen as a double star by means of Professor Van Biesbroeck's interferometer.

George W. Ritchey was first to use the telescope successfully for photographic work, and in 1900 and 1901 obtained pictures of the moon, of star clusters and nebulae that are among the best ever taken, either before or since. The crown and flint lenses of the achromatic objective had been figured by the maker to focus the green and yellow rays to which the eye is most sensitive, but by interposing a color filter and using panchromatic plates (which are sensitized to the visual rays) particularly sharp photographs are obtained.

In 1904 and 1905 a great many of these star photographs were obtained by Dr. Frank Schlesinger, later director of Yale Observatory, and used in the determination of stellar parallaxes. This determination is made by photographing a star at six-month intervals, the parallax being reduced from the sharp plates by measuring the apparent movement of the star with respect to its background.

In 1930, an experiment of another sort was made with the great refractor, when Professor Joel Stebbins, director of the

Washburn Observatory of the University of Wisconsin, used it in connection with a new and sensitive photoelectric photometer, designed to measure the brightness of stars. The photometer used by Dr. Stebbins consisted of a quartz bulb coated on the inside with a powder containing sodium or caesium, metals which have the property of generating tiny electric currents when light falls upon them. The amount of the current is proportional to the intensity of the light; hence a sensitive galvanometer gives a measure of the light from any except the faintest stars.

The Yerkes Observatory, like Lick, is built up around its one great instrument, but its equipment is by no means limited to the 40-inch refractor. In the southeast dome of the observatory is a 24-inch reflector which has the distinction of having been figured by Professor George W. Ritchey, who also supervised the construction of the mounting. When used for photographic work, stars of the ninth magnitude, which are only a thousandth as bright as stars of the first magnitude and are completely invisible to the unaided eye, may be photographed in one second with this telescope. An exposure of three hours will yield portraits of stars that are invisible even in the 40-inch refractor.

Also at Yerkes Observatory is the Kenwood equatorial refractor of 12-inch aperture originally used by Dr. Hale in his private Chicago observatory. This instrument, made by Brashear, has two objectives, one for visual work, the other for photography. They are now both arranged on a twin mounting.

The staff of Yerkes Observatory includes fifteen scientific workers and ten technical employees. It was at Yerkes that Dr. E. E. Barnard, famous for his studies of the Milky Way, made his discovery of "dark" nebulae. Here also were made the first measurements of the heat of the stars, and the first determinations of the motions of the hot helium stars by Dr. Edwin B. Frost, second director of the observatory, and Dr. W. S. Adams, now director of Mt. Wilson Observatory. The remarkable camera lenses for wide-angle photography, designed by Professor Frank

E. Ross, have been developed at Yerkes, and are now used at several of the large observatories.

In recent years the staff of the Yerkes Observatory has been greatly strengthened by the addition of several world-famous scientists, including Professor Gerard P. Kuiper, formerly of the University of Leiden; Professor S. Chandrasekhar of Madras, India, and a former fellow of Trinity College, Cambridge, England; and Professor Bengt Strömgren of the University of Copenhagen, Denmark.

The present director at Yerkes is Dr. Otto Struve, professor of astrophysics at the University of Chicago and great-grandson of the famous Russian astronomer, F. G. W. Struve.

III

The site of Yerkes Observatory was one of the earliest to be chosen with a view not so much to the decoration of a college campus as to the selection of a spot where seeing was exceptionally good. Dr. Hale conferred with many astronomers, and investigated more than twenty sites before he was satisfied. His final selection, a tract on Lake Geneva about 76 miles from Chicago and a mile and a quarter from the post office of Williams Bay, Wisconsin, has proved exceptionally successful.

It is, however, somewhat farther north than is desirable for the largest view of the heavens. Yerkes needed a more southerly eye as well—and now through the bequest of a wealthy Texan, the late W. J. McDonald, and the cooperation of the Board of Regents of the University of Texas, it has been supplied. Mr. McDonald provided the Texas University with about $900,000 to found an observatory in his name. By an agreement reached in 1932, the director of Yerkes Observatory is to serve as director also of McDonald Observatory, and the University of Chicago provides the necessary scientific staff.

It is no small instrument which this arrangement makes available to the astronomers of Yerkes Observatory. McDonald Observatory, now completed, is located 6,800 feet above sea level, on Mt. Locke in the Davis Mountains, some 200 miles east of

El Paso. Its principal instrument is an 82-inch reflector, with optical parts and mountings constructed by Warner & Swasey. Next to the Mt. Wilson and Mt. Palomar telescopes, it is the largest reflector in the world.

The mirror is of Pyrex glass, 13 inches thick and weighing nearly 3 tons. Cast at Corning, New York, it required more than six months to cool. Grinding, figuring and polishing, which began October 30, 1934, were completed late in 1938. The mirror is coated with aluminum, and the instrument is equipped with three optical combinations: Prime focus, Cassegrain and Cassegrain coudé.

Research began at McDonald in the summer of 1938. The staff consisted of Dr. W. A. Hiltner, assistant director, and three research associates. The principal work is the investigation of stellar spectra, stellar photometry and research on nebulæ. It will ultimately consist of a vast extension of the Yerkes program; a fruitful coupling of two of America's finest telescopes in a synchronous exploration of the heavens.

IV

Now we must go back, for the moment, to the year 1902, when Dr. George Ellery Hale, directing with magnificent adroitness the growing and powerful Yerkes Observatory, was nevertheless beginning to busy himself with a new and even larger idea. It was a plan to erect, somewhere on a mountaintop, a special station for observations of the sun.

Early in that year the Carnegie Institution of Washington was organized, through the foresight and generosity of Andrew Carnegie. Committees were appointed to report on the requirements of the different sciences, in order that the Institution might give help where such assistance was most needed. The secretary of the committee for astronomy was Dr. Hale, and after study the committee made two recommendations: (1) a southern observatory for special stellar observations, and (2) a solar observatory to be located at a high altitude.

The report was accepted by the Carnegie Institution. Dr. Hale, Dr. Benjamin Boss and Dr. William W. Campbell were thereupon appointed a special committee to study the proposals in detail. Prof. W. J. Hussey, of Lick Observatory, was engaged to make a study of possible high-altitude observatory sites in California and Arizona, and in 1903 he visited a number of places, finally recommending Mt. Wilson as the best available spot.

The story goes that Dr. Hussey's report on Mt. Wilson was so optimistic Dr. Hale decided to check up on it himself. Taking along a small portable refractor of 3¼ inches aperture, he arrived one summer day in 1903 at Pasadena. As luck would have it, the day was foggy, but Hale, undaunted by the weather, immediately set out up the mountain. The fog continued into the evening as he climbed. The chances for seeing anything seemed remote indeed. But the astronomer pressed on, and suddenly as he neared the summit, the cloud blanket rolled away. Spellbound the seeker stood gazing at the richness of the heavens from the mountaintop: a dramatic, prophetic forecast of the astronomical mysteries later to be revealed there. Dr. Hale reported to the Carnegie Institution at Washington a few days later that the finest place for a new observatory in America had been found.

His report was accepted, and Hale was informally offered the directorship of the new solar observatory. But there was delay in arranging for funds. Impatient, Hale returned to Pasadena in December of the same year, bringing with him a small refractor from the Yerkes Observatory. He took along a carpenter to repair a log cabin on Mt. Wilson's summit. For weeks he hiked up and down the mountain trail, carrying his own supplies, and at night studied the skies. On his own initiative, he presently raised money to bring out from the Yerkes Observatory another instrument—a 6-inch, 60-foot coelostat telescope. Along with the bigger telescope came his assistant, Ferdinand Ellerman, and in effect, Mt. Wilson Observatory was already a going institution. Delighted with Hale's early results, the Carnegie Institution of Washington granted funds in April,

1904, which formally established what is today the largest and perhaps most important institution of its kind in the world.

One of the first major instruments set up at Mt. Wilson was the curious Snow "horizontal" telescope, obtained from Yerkes Observatory. It had been designed under Hale's direction for the University of Chicago, but conditions were not right for it at Williams Bay. The telescope is called "horizontal" because its body is immovably fixed on the ground, and the only part in motion is a small coelostat mirror which, revolving slowly on an equatorial, clock-driven mount, receives the light of the sun and reflects it to a plane mirror. This in turn passes the beam into the telescope (see page 135). Such apparatus with proper adjustment will catch the image of the sun all day long, while the astronomers work at ease, the light coming to them as steadily as if the sun were standing still.

For more than a dozen years photographs of the sun were taken daily with this instrument. Recently a 30-foot spectrograph has been added, and the telescope is still used on occasion for solar observations.

It is outmoded, however, by two "tower telescopes," which work on the same principle except that they are vertical instead of horizontal. At the top of each tower a clock-driven coelostat catches the light of the sun and passes the beam to a second, plane mirror, which casts it downward through a lens of great focal length. Beneath each tower is a well, in depth half the height of the tower. In these subterranean chambers, sheltered from abrupt changes of temperature, from vibration and the effects of wind, are the spectrographs and other solar instruments.

The smaller tower telescope employs a lens of 60-foot focal length, and is used daily for direct solar photographs and spectroheliograms showing the distribution of hydrogen and calcium clouds over the surface of the sun. The newer and larger tower is 150 feet high, and has a lens of that focal length, used with a spectrograph 75 feet long which extends to the bottom of the well at the foot of the tower.

On account of its great height (magnification here being

proportional, as in other telescopes, to focal length) the 150-foot telescope forms an image of the sun 17 inches in diameter. It is such an instrument as old Hevelius himself might have envied, and rivals in length the enormous instruments of Christiaan Huygens, while surpassing them many-fold in usefulness. For with an image 17 inches in diameter, the sun is revealed in all his glory. Here the famous spots and other phenomena can be studied individually by the spectroheliograph, spectrohelioscope, coronagraph and spectrograph, to say nothing of a dozen other instruments for measuring heat, surface temperature, magnetic and electrical fields, and chemical composition.

Remarkable as these instruments are, it was not like Hale to be long content with them. In addition to solar instruments, Mt. Wilson needed large and powerful movable telescopes, and the energetic young director (he was then thirty-six) set out to get them.

Lying in the optical shop at Yerkes Observatory was a huge mirror, 60 inches in diameter, the personal property of Dr. Hale, started soon after that institution was dedicated in 1897, but never finished. It had been the director's ambitious plan to have at Yerkes the largest reflector in the world as well as the largest refractor. He had obtained the glass (purchased by his father) in France, and the work of grinding it had been started by George W. Ritchey.

But the cost of finishing such a large telescope began to tax the financial capacity of the observatory. Moreover, before the mirror had been finished, interest in the new Mt. Wilson Observatory had focused the attention of Dr. Hale, Professor Ritchey and members of the staff of Yerkes on the advantages of the mountain site. The unfinished 60-inch mirror was presented to Mt. Wilson Observatory, and there Professor Ritchey brought it successfully to an excellent figure and silvered it.

The mounting was provided for with funds from the Carnegie Institution, and observations were begun in 1908. For the 60-inch mirror Ritchey designed a mounting which, under various names, usually that of "modified Cassegrain" or "coudé,"

has since been adopted for several large telescopes, including the 100-inch. It can be used either in the Newtonian or Cassegrainian form. In the former, it has a focal length of 25 feet. In the latter the focal length is increased to 80 feet by the convex second mirror, which reflects the light back to a plane mirror over the center of the main speculum. This speculum is not pierced at the center, as in the case of standard Cassegrains. Instead, the plane mirror passes the image out to an eyepiece at the side near the lower end of the tube. By proper adjustment, a third or "polar Cassegrain" arrangement is possible, the light passing through a tube in the hollow polar axis into a constant-temperature room adjoining the dome on the south. In this case the focal length is 150 feet.

For nearly ten years the 60-inch was the largest telescope in the world, and it is still the favorite of many astronomers at Mt. Wilson, who find its performance excellent, even at times when the seeing for the 100-inch is bad.

V

When the 60-inch telescope was built it was considered a great and perhaps foolhardy experiment. No one could say whether the wider aperture would not submit the instrument to such atmospheric aberrations as to make it useless. How much more of a gamble then, was a 100-inch telescope, when in 1906 a Los Angeles business man, John D. Hooker, agreed to provide $45,000 for the mirror of such an instrument! At that time there was no interferometer at Mt. Wilson to test the seeing.

Mr. Hooker at first had not counted on a mirror of 100 inches. His original gift was for an 84-inch mirror, but before such a glass could be ordered he increased the sum to provide for a mirror so gigantic that it would not likely be surpassed, at least in a generation.

In that day the project seemed fantastic, considering how difficult only the simplest part of the task, the making of the glass disc, would be. Every optical glass establishment in the

world was canvassed by Dr. Hale before one could be found that would even consider such an undertaking. Finally, the St. Gobain Glass Works, situated in the Forest of St. Gobain, France, agreed to try to cast it.

The glass cast for the 60-inch telescope was the largest that could then be made from a single pot of glass. It was 8 inches thick and weighed about a ton. But the disc for the Hooker telescope had to be 13 inches thick, nearly 9 feet in diameter, and in weight approximately 5 tons.

After some experiments, the St. Gobain glass-makers made a large mold, and heated up three huge pots of glass. These were then dumped in quick succession, and the mold covered over for a long session of cooling. Months passed. The glass went through its annealing stages, and finally was cool enough to be broken out and examined.

To the enormous dismay of all concerned, the disc was found to contain sheets of bubbles. The authorities at Mt. Wilson decided to bring the disc to Pasadena anyhow, for a more detailed examination. The results were not promising, but after further attempts by the glass founders to produce a better disc, it was decided to give the original disc a preliminary spherical figure to test its qualities. Professor Ritchey finished these tests in 1912. The bubbles, which at first had brought disappointment, were found to be no drawback at all; they did not come near enough to the surface of the glass to interfere, and the glass seemed to be free from internal strains.

The work of figuring the mirror to its final paraboloidal curve was then commenced. It required four more years of the most exacting work. The finished mirror is actually 101 inches in diameter, about 13 inches thick, and weighs 4½ tons.

Mr. Hooker had provided only for the construction of the optical parts of this giant. There were still required half a million dollars to pay for a suitable mounting—one so delicate that it would swing this 4½-ton piece of curved glass at the touch of a hand, so smooth that a clock could move the telescope without dislocating images of the stars upon a photographic plate.

This money was supplied by the Carnegie Institution of Washington, when Andrew Carnegie doubled its endowment in 1911. When finally finished in 1917, the telescope weighed 100 tons and had cost $600,000. The mounting had been designed by the observatory staff and most of the smaller parts were made in the machine shop at Pasadena. The heavy castings were manufactured by the Fore River Ship Building Corporation at Quincy, Mass., and the tube was shipped in large sections by steamer around Cape Horn to Los Angeles Harbor.

The telescope proper is hung in a rectangular steel yoke which forms part of the polar axis. The problem of obtaining flawless bearing action was solved by floating the weight in mercury. The telescope is driven by a clock mounted in a room under the south tier. By means of a worm gear, it drives a 17-foot wheel attached to the polar axis. So smooth is the action, almost no lag or jar is to be noticed even when the telescope is used in the modified Cassegrain or coudé form, which gives a total focal length of 250 feet.

The focal length of the large mirror is 42 feet. At this focus it is used for photographic or spectrographic work, the plate for photography usually being placed at the Newtonian focus. Two modified Cassegrainian forms are available for spectrographic work, as in the 60-inch. When the telescope is used in the first manner (that is, with a second small mirror to reflect the image out of the tube into an eyepiece at the side), the focal length is 134 feet. When it is used in the polar coudé form, the beam being reflected south through the polar axis to the constant-temperature room below, the focal length is 250 feet (Fig. 45). The magnification of the mirror system alone (without eyepiece) consequently varies from about 50 to 300 diameters, depending on the focal length. With proper eyepiece it could theoretically be stepped up several thousand diameters, but of course such magnification is impractical because of imperfect seeing.

The greatest advantage of such a telescope is its enormous light-gathering power. It collects about 200,000 times as much light as the unaided eye, and is capable of "seeing" photo-

graphically about 1,500,000,000 stars, whereas the eye alone can see only five or six thousand in the whole sky.

The resulting advances in knowledge are often such as to make newspaper headlines, despite the enormous complexity of the subject and the technical nature of the programs being carried on at Mt. Wilson. This observatory has one of the finest staffs of professional astronomers anywhere on earth, now

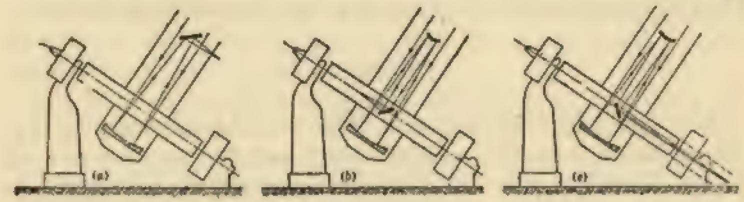


Fig. 45

Three Ways in Which the 100-inch Telescope at Mt. Wilson May Be Used: (a), As a Newtonian; focal length 42 feet. (b), As a modified Cassegrain, or coudé; focal length 134 feet. (c), As a polar Cassegrain; focal length 250 feet.

headed by Dr. Ira S. Bowen (Dr. Hale was made honorary director in 1923 and retired from active research some time before his death in 1938. He was succeeded by Dr. Walter S. Adams, who retired in 1946). The staff includes such men as Edwin Hubble, Seth B. Nicholson, Edison Pettit, Alfred H. Joy, Adriaan van Maanen, and others whose work is making history. Moreover, to this magnificent institution and its giant instruments scientists come every year from all over the earth. Among the research associates of Mt. Wilson are Sir James Jeans, the famous British astronomer, cosmologist and mathematician; Dr. Henry Norris Russell, director of the Princeton University Observatory, and Prof. Joel Stebbins, director of the Washburn Observatory of the University of Wisconsin.

Albert Einstein came to this observatory to find data in support of his famous theory of relativity. Here came the Abbé Lemaitre for information upon which his theory of the explod-

ing universe is based. To this mountain in California, with its great eyes and their auxiliary instruments (which now include a 50-foot interferometer, a 10-inch photographic refractor and almost innumerable spectrographs, spectroheliographs, spectrohelioscopes, thermocouples, photometers of various kinds and other instruments), scores of scientists perhaps less well known to the public, but nevertheless leaders in the astronomical world, make annual pilgrimages to use the instruments or to examine the photographic records of the heavens accumulating there.

VI

While it might be said that today's giant observatories are all in North America, it is certainly untrue that they are all in the United States. Our Canadian cousins have been quick to follow the lead of the United States in matters of astronomy, and to add a few ideas of their own. The result is that Canada now has two major observatories, with instruments that rank among the first half dozen in the world.

Seven miles north of the city of Victoria, British Columbia, there is a reflector that until recently dwarfed every telescope in existence save one. This is the instrument of the Dominion Astrophysical Observatory, operated by the Department of the Interior of the Federal Government of Canada—a 72-inch giant which the joint product of the St. Gobain Glass Works, the genius of the late American telescope-maker John A. Brashear and his skilful son-in-law, J. B. McDowell, and the capacity for building fine mountings developed by the American firm of Warner & Swasey at Cleveland.

The old Dominion Observatory at Ottawa was originally founded as an aid in surveying Canadian territory, particularly the western portions of it. In the colonization of these lands, one of the obvious first needs was a survey of the boundaries into townships and sections, and since accurate surveys are impossible without astronomical data, the astronomical branch was created in the Department of the Interior.

The first Chief Astronomer of Canada was the late Dr. W. F.

King. Through his efforts a small observatory was erected on the Experimental Farm at Ottawa in 1905, equipped with an excellent 15-inch refractor provided with a micrometer, photometer, solar and stellar cameras and a spectograph.

But it was soon perceived that a larger institution was needed to perform the work of the observatory and keep up with the scientific procession. Early in 1913, at the suggestion of Dr. J. S. Plaskett, director of the observatory, the Canadian Government provided funds for a large telescope. W. E. Harper, later director of the observatory, was sent out to examine several possible sites for the new institution.

The final choice fell not upon a mountain, as had been expected, but on a small hill locally called Little Saanich Mountain, now renamed Observatory Hill, near Victoria. Unlike such elevated sites as Mt. Hamilton and Mt. Wilson, this location is only 730 feet above sea-level, but so varied are the tricks of good seeing that the place has been found by experience substantially to equal any other on the continent.

The observatory is built at present around its main instrument, the 72-inch reflecting telescope, specifications and design of which are due to Dr. Plaskett. The plans were completed in the autumn of 1914, and construction of the mounting was commenced at once. This part was finished and temporarily erected at the works of Warner & Swasey in Cleveland in 1916, and later shipped to Victoria for permanent installation in its new home.

It was more than a year and a half before the mirror itself was ready. Part of the delay was the old difficulty of casting the glass, which had been undertaken by the St. Gobain Works, the ill-fated institution over which even then the war-clouds were hovering.

The casting and annealing of the disc was completed on the first of June, 1914. It left Antwerp en route for the works of the John A. Brashear Company at Pittsburgh only a week before war was declared; by only this small margin did the glass become the mirror for one of the finest telescopes in the world. A 55-inch flat, ordered from the Gobain Works for use in test-

ing the figure of the mirror during polishing, was never made. The famous works, mother of so many important telescopes, went down in flames and a rain of steel a few days after the outbreak of the First World War.

The 72-inch mirror was completed at Pittsburgh by Mr. McDowell and his chief optician, Mr. Fred Hegemann, and was placed in the mounting awaiting it at Victoria in April, 1918. It has a focal length of 30 feet, and is pierced in the center for use as a Cassegrain, in which form its focal length is 108 feet. It has eyepieces designed to provide magnification over a range of from 120 to 5,000 diameters, and three finders are attached for picking up and centering the field.

The instrument is used mainly for photography and spectrographic work. The radial velocities of 1,500 stars, and the spectroscopic parallaxes of 1,000, have been determined with it.

VII

The other Canadian giant, still so new its potentialities have hardly been realized, is the 74-inch reflector at the David Dunlap Observatory of the University of Toronto.

This huge telescope, largest in Canada and second largest in the world when it was installed in 1935, was made possible through the generosity of Mrs. Jessie Donalda Dunlap, who provided it as a memorial to her husband. For more than twenty-five years Dr. C. A. Chant, beloved Professor of Astrophysics at the University of Toronto and first director of the observatory, had been lecturing before scientific bodies, groups of amateur astronomers and laymen's societies, urging that such an instrument be made available to Canadian astronomers. It was his enthusiasm that finally bore fruit in Mrs. Dunlap's gift.

The telescope was made by Sir Howard Grubb, Parsons & Company in England. The mirror, of Pyrex glass, was poured at Corning, New York, and sent to England to be ground and figured.

One of the interesting devices on this telescope is the huge iris diaphragm, which opens and shuts like that of a camera,

from the full aperture of 74 inches down to a circle twelve inches in diameter, at which point the leaves close around a central core. This is useful not only in adjusting the aperture to the quality of the seeing, but also is an aid to keeping the mirror temperature uniform, a major problem at Toronto, where the very changeable weather provides difficulty for telescope-makers. Because the climate, cold, then warm, causes the mirror to sweat and ruins the silver coat, all sides of the mirror are packed with absorbent cotton. The chamber, of which the silvered surface forms the bottom, is nearly airtight when the iris is closed. In addition, a hothouse heater cable is clipped to the inside of the mirror cell, and provides enough heat under ordinary conditions to keep the mirror dry.

The telescope has now been used satisfactorily through several winters "in the most rigorous climate in which it has ever been attempted to operate a large reflector," reports Dr. R. K. Young, director of the observatory. The work has principally been observation of the radial velocity of stars in and near the Kapteyn areas. More than 3400 spectrograms have been obtained, measured, and the results tabulated for publication. Observation of eclipsing and spectroscopic binaries has been started. More than 350 photographs have been made in a search for variables in globular star clusters.

Chapter XV

SOME FAMOUS AMERICAN TELESCOPE-MAKERS AND THEIR WORK

I

THE story of telescope-making in America begins in a kitchen in Cambridgeport, Mass., where in the spring of the year 1844 a fashionable artist of forty and his seventeen-year-old son sought to make a cake of bell-metal into a telescope mirror.

The artist was Alvan Clark, descendant in the seventh generation of Thomas Clark, mate of the *Mayflower;* a farm boy who became an engraver and an artist, and who finally, through a curious twist of fortune, turned to the making of telescopes. The son was his eldest, George Bassett Clark.

The entry of the Clarks, father and two sons, into the business of making telescopes for the greatest astronomers of Europe and America came about in this way:

George Bassett Clark in 1844 was a student at Phillips Andover Academy, where he was studying to be a civil engineer. Naturally he had taken up the subject of astronomy, but unlike others of his class, had been peculiarly fascinated by the mechanical problems of telescope-making. One of his firmest resolutions was that, at the earliest opportunity, he would obtain some metal and make a small telescope.

Then an unexpected, providential thing happened. In calling his fellows to lunch one day one of the students swung the old-fashioned dinner bell of the Academy with such zeal that it was broken. Young Clark, who remembered that the great Newton had made his reflecting telescopes of bell-metal, carefully picked up the pieces and took them home with him. Later

he melted up the metal and cast it into a disc in the kitchen of his father's home at Cambridgeport, and began the laborious business of making it into a mirror. The disc was only a little more than five inches in diameter, but the task nevertheless proved difficult. The elder Clark, pausing from his painting to give advice, soon became even more engrossed than his son in the struggle with the unmanageable metal. Together they worked on it, grinding, polishing, testing, polishing again, until finally the true paraboloidal figure appeared. It was a mirror at last!

But the triumph was short-lived. No sooner was the job done than tarnish began to appear. By this time deep in the new game, the elder Clark then perceived, as he tells in an autobiography written years later at the request of a friend, why the mirror type of telescope, a few years earlier in great vogue, was being abandoned by astronomers. It was the tarnish—in his opinion an insurmountable obstacle.

Clark suggested to his son that they might try their hands at an achromatic refractor, like the great telescopes that had recently been made in Europe by that master, Fraunhofer, and which were still being made, bigger and bigger, by Fraunhofer's successors. Such telescopes, he pointed out, never corrode; once finished properly they last indefinitely, and are beautiful to behold as well as convenient to use. George Bassett Clark had some doubts; the refractors were better, but he had heard of the extreme difficulty of making them. It was an art which seemed peculiarly adapted to European craftsmen; did it seem reasonable that anyone in America, particularly without the advantage of Fraunhofer's secrets, could learn it?

The Clarks experimented. Using such glass as they could obtain cheaply in Boston, they made a small objective. The elder Clark studied the new art assiduously, and at last the figures began to come. But he was nevertheless tormented by doubt. The object-glass must be so very perfect to succeed; how could any man, without apprenticeship in the shops of the great masters of telescope-making abroad, possibly excel in so difficult an art?

Then came the event which gave him confidence. The great

15-inch refractor was installed at Harvard Observatory—the telescope of which the object-glass alone cost the enormous sum of $12,000, and which was one of the biggest and most perfect in the world. No sooner had it been placed in the observatory than Alvan Clark was eager for a look at it—more especially for a look *through* it. He applied to the director; permission was given, and in the end the portrait painter of Cambridgeport stood one day at the eyepiece of the world's most marvelous telescope.

And what was this? The greatest glass in the world was not perfect! The errors of figure were very small, yet Alvan Clark could locate them at a glance!

Clark went home that day filled with hope and courage. If European telescope-makers could get $12,000 for an object-glass—and one which even at that was not quite perfect, then a certain erstwhile American painter of portraits could make better ones, and probably get as much or more.

His first job was to remake several old glasses he had picked up here and there, at second-hand stores and from junk dealers. Days of grinding, polishing, testing. Sometimes the remade discs came out well—beautiful alike to the eye of the artist and the telescope-maker. Sometimes (more often, alas!) the stubborn glass was warped, filled with striæ, impossible of improvement. But with each disc came greater confidence and skill. Finally he felt the time had come to make a new objective, with glass such as the European makers employed.

The first glass discs brought from abroad on his order were 5¼ inches in diameter. A little later he made another telescope, with discs 8 inches in diameter which he had found in New York. Clark knew that these telescopes were excellent instruments; equal to or better than those of the European makers. But who else would believe it? Telescope-making was an industry new not only for Alvan Clark and his sons but also for America. Moreover, there was little demand in this country for such instruments. Colleges and observatories were buying theirs abroad, nor could they be convinced that an American was able

to make a telescope even good enough to repay the trouble of testing.

Now the elder Clark was a man called by his destiny. He did not give up simply because recognition was slow in coming. In 1851, after seven years of telescope-making had failed to attract attention in this country, he wrote to the Rev. W. R. Dawes in England, telling of double stars he had been able to discover with his small telescopes. Dawes wrote back, astonished. Where had these fine small telescopes been obtained? Why, Clark had made them himself. In fact, said Clark, the making of fine telescopes was his main interest; the discoveries were only, so to speak, incidental.

The correspondence continued, grew in volume. In 1852 Clark reported to Dawes that with a glass only 4¾ inches in aperture he had discovered two more double stars, of which one was *8 Sextantis.* The following year he finished a new telescope of 7½ inches aperture, and immediately wrote Dawes that he had seen the dim companion of the star *95 Ceti.*

This was the final achievement that fetched Dawes's curiosity. He wrote back at once that he would like to buy that new glass, but first he wanted a thorough test of it. Enclosed was a list of difficult double stars discovered by the astronomer Struve in Russia. Would Clark please be good enough to see if his glass would resolve them?

Clark turned his telescope to the skies the very night the letter arrived, and in a few days was able to send the preacher-astronomer of England such a complete and excellent description of Struve's double stars that Dawes was delighted. He purchased the telescope by return mail, and afterwards bought four others, one of which, an 8-inch, soon came into the hands of William Huggins. It was this telescope, one of the first half-dozen made by Alvan Clark, that was used by Huggins in his pioneer work with the spectroscope. This same telescope, out of Cambridgeport, Mass., first transmitted the light of a star to a prism, and thence to a photographic plate, and thus enabled Huggins to be first to wed the camera and the spectroscope. Another of these early Clark telescopes came into the hands of

the English astronomer Knott; others the Reverend Dawes kept for himself, and so pleased was Dawes with his American "find" that he invited Clark to visit him in London and meet the notables of the astronomical world.

Clark accepted the invitation in 1859, carrying along with him an equatorial mounting and two object-glasses, one of 8 and the other of 8¼ inches. He visited Dawes for six weeks in London. They went together to the Royal Observatory at Greenwich, and later attended a meeting of the Royal Astronomical Society. Clark saw and talked to the kings of the astronomical world; hobnobbed with Lord Rosse and chatted with the astronomical hero, Sir John Herschel. Dawes was as pleased with the personality of the American telescope-maker as with his telescopes. Afterward he frequently published reports of discoveries with Clark telescopes in the monthly notes of the Royal Astronomical Society. Orders came from abroad for Clark telescopes and more Clark telescopes. The builders of Cambridgeport, now working under the name of Alvan Clark & Sons, were busy.

Their fame spread. It traveled from England over to the Continent. More wonderful still, it came back to America. Even the skeptical astronomers of Boston and New York heard about Clark and began to desire his instruments.

II

Now the time had come for greater triumphs. In 1860 Dr. F. A. P. Barnard, president of the University of Mississippi (later to become president of Columbia University in New York), ordered a telescope from the Clarks for the observatory at Mississippi University. It was to be a good telescope, and moreover, it was to be the biggest refracting telescope anywhere in the world. The object-glass was to be no less than 18½ inches in diameter.

It was an almost breath-taking order in 1860! Such a glass, if well made, would establish for good and all the reputation of the telescope-makers of Cambridgeport. But first they must

have larger quarters. Alvan Clark sold the house in which he had begun as a telescope-maker, and with the proceeds, plus the profits from earlier telescopes and some borrowed money, bought an acre and a half of ground and set up the first telescope factory in America.

It was a real factory, equipped with all manner of devices originated by Clark and his elder son, George, who was especially gifted in mechanics. Important among these devices, besides the necessary grinding machines, were several aids used to protect glass during the working. A lens in the process of grinding was placed on its edge in a small car, which ran on a track. Every night the car with its precious cargo was run into a fireproof safe so that no matter what might happen to the factory the lens would be secure. The safe itself was connected with an alarm placed in Alvan Clark's bedroom.

Another innovation was the testing chamber, an underground vault 230 feet long, constructed in such a manner as to protect it from vibration, dust, changes in temperature, and other disturbing influences. There the delicate tests for final figure were made, with devices and methods which Clark himself had originated or improved.

Adjoining the factory Clark built a residence and an observatory. The observatory was equipped with an equatorially mounted Clark telescope, with circles, driving clock and micrometer. Overhead was a great dome, revolving on cannon balls.

III

About the beginning of the year 1862 the glass for the University of Mississippi telescope arrived from Messrs. Chance Brothers & Company, of Birmingham, England. Within a year the new lens was ready, and it fell to the lot of Alvan G. Clark, the younger son, to make an actual test of it by looking for double stars.

This momentous test was to make history. On the very first night that any man had looked through the lens, Alvan G. Clark turned it toward the great star Sirius, and there saw

a marvel that had been predicted by the astronomer Bessel, but which to that day no person had seen—the "dark" companion of Sirius, which was thereby proved to be a double star.

It was, needless to say, a find of the first rank. The Clarks communicated immediately with Harvard Observatory, which was then as now a distributing point of astronomical information. On a fine night not long afterward Professor George P. Bond was able to see the dark companion with the Harvard 15-inch refractor, thereby confirming the discovery. For this discovery and his part in the production of the 18½-inch lens the French Imperial Academy of Sciences awarded Alvan G. Clark the Lalande Prize for 1862, a gold medal and $120 in gold.

But now the already famous glass, complete and ready for delivery, had no home. The Civil War had broken out, and cut off all communication with the South. In 1863 it was purchased by the Chicago Astronomical Society, and later was used by Sherburne Wesley Burnham, the American amateur astronomer who attracted world-wide attention by his discoveries of new double stars. By profession Burnham was a court stenographer, but in the evening hours he was one of the most assiduous searchers of the skies. In 1906 the Carnegie Institution published a complete list of double stars compiled by him in the northern hemisphere and south to the 31st parallel—and the total number in this list was 13,665 stars!

As for the Clarks, they had little time to dwell on the triumphs of the large glass, for new orders deluged them. Six times since 1860 the firm has been called upon to build the largest telescope in the world, each time increasing the aperture from one to six inches over that of the last. The largest refracting telescopes in America today were made by the Clarks, including the Lick and Yerkes refractors, and the famous 26-inch instrument of the United States Naval Observatory, with which Dr. Asaph Hall discovered the satellites of Mars in 1877.

The Naval Observatory glass was ordered in the summer of 1871 and finished in 1872, almost exactly a year after the glass from which it was made had arrived from abroad. The Clarks received $46,000 for it. In the same year they made another

26-inch telescope, a companion to the one at Washington, for Leander J. McCormick, son of the inventor of the reaper, who later placed it in the Leander McCormick Observatory of the University of Virginia, where it is now used for extensive research in stellar parallaxes.

In 1879 the Clarks made a telescope of 30 inches aperture for the Russian Government Observatory at Pulkowo. Russia sent its great observer of the day, Otto Struve, to examine the glass here upon its completion, and he was the guest of Alvan Clark at Cambridgeport, in the house adjoining the workshop.

In 1880 work was begun upon a still larger telescope—the 36-inch giant of the Lick Observatory in California. The contract for these lenses was placed with the Clarks only after the Lick trustees had canvassed every telescope-making establishment in the world, to determine which could do the job best. The instrument required seven years to build, and cost $50,000 exclusive of the mounting. It was shipped to California in December, 1886, in a special car and accompanied by an entourage of sixteen persons. Alvan G. Clark went with the lens on its journey across the continent, and remained at Mt. Hamilton until the shining discs had been placed safely in their mounting.

Less than a year after the completion of the great Lick telescope, Alvan Clark died, at the age of eighty-three. George B. Clark, the elder son, had undermined his health as early as 1874 by excessive application to his duties in the shop, and after a protracted illness he, too, died on December 30, 1891. Alvan G. Clark followed them six years later, in his sixty-fifth year, on June 9, 1897. Thus within a decade death wiped out completely the first dynasty of telescope-makers of America.

IV

The Clarks were dead, but not the firm of Alvan Clark & Sons, of Cambridgeport, nor the art of making fine telescopes in America.

In 1873, when the increasing age of Alvan Clark made more help necessary, the firm had been joined by a young Swede, Carl

Axel Robert Lundin. He was then twenty-three, a patient, methodical, careful workman—just the type for telescope-making under the training of the Clarks. He rapidly became more than an employee; soon he was a co-worker and friend. Upon the death of Alvan G. Clark, Lundin continued the business.

And it was no inconsiderable business the Clarks had left. Orders for Clark telescopes continued to pour in, as the many notable instruments they had made achieved new triumphs.

To Lundin, in fact, fell the greatest opportunity of all—the making of a refracting telescope so large that there probably never will be one larger. When the Yerkes Observatory was being constructed, Dr. Hale, the director, learned that the Clark firm had on hand some fine pieces of glass large enough for a forty-inch refractor. Promptly he took up the matter with Lundin, with the result that the great refractor at Williams Bay bears on its plate the name of Alvan Clark & Sons.

Lundin also made the 24-inch refractor (aided by Alvan G. Clark) for the Lowell Observatory at Flagstaff, through which Dr. Percival Lowell obtained the major part of his information about Mars and the other planets, and the data which revealed the existence of the trans-Neptunian planet Pluto. It was not with this instrument that the new planet was spotted, however, but with a Clark photographic telescope of 13 inches aperture. The Clarks have built very few reflecting telescopes. The 42-inch mirror at Lowell Observatory was made by Lundin in 1909.

Carl Lundin was found dead on the floor of his bedroom on the morning of November 28, 1915, a victim of heart disease. The firm of Alvan Clark & Sons carries on, however, under able management.

V

While Alvan Clark and his sons were busy establishing the art on a professional basis, there were also amateur telescope-makers in America, contributing a great deal to the progress of the craft, as amateurs are still doing today.

One of these non-professionals was the astronomer Dr. Lewis Morris Rutherfurd. In the autumn of 1856 Rutherfurd built a small observatory at Second Avenue and Eleventh Street, New York, equipping it with a refracting telescope of 11¼ inches aperture made by Alvan Clark & Sons.

Rutherfurd was interested mainly in the development of astronomical photography, and determined to make a telescope that would be corrected for the photographic rays—a type of instrument almost unknown in his day. After much labor he finally achieved an object-glass the same size as his Clark objective. This was completed in 1864, and in that year he proved its excellence by photographing the moon so beautifully that the negatives could be enlarged to prints more than two feet in diameter without losing detail. Large prints made by Rutherfurd with this home-made 11¼-inch photographic refractor are still preserved in the New York Public Library, and the telescope itself, equipped with a driving clock, micrometer and spectroscope, is the main instrument of the Columbia University Observatory, where Rutherfurd sent it in 1883.

Equally prophetic of the future of telescopes were the instruments made by Dr. Henry Draper for his small private observatory at Hastings-on-Hudson. Like his father, Dr. John Draper, Henry Draper was intensely interested in astronomical photography. He early perceived that the use of photographic plates would require more light on the image, and hence larger apertures.

With this problem in mind he visited Lord Rosse at his observatory at Parsontown, Ireland, and learned from that great maker of telescopes the secret of grinding and figuring reflectors. He returned home in 1857, determined to construct a telescope similar to that at Parsontown, but smaller, and one especially adapted to photography.

Using speculum metal made after Lord Rosse's formula, he cast a disc about 1860 and made a machine to grind it. All during 1861 Draper struggled with the brittle and stubborn metal, stealing time from his medical duties and his sleep. He found that his machine tended to polish the speculum metal

in rings of different curvature, and was very slow. He tried to improve it by many means, even to the use of acid and electrical currents, but still the speculum metal refused to yield a good mirror.

Almost discouraged, he learned one day the success of Foucault in making a speculum of glass covered with silver. With renewed zeal he turned to glass discs. He improved his polishing machine, experimented with silvering processes, and finally, after more than 100 mirrors had been fashioned, varying in size from less than an inch to more than 16 inches, he made one that performed satisfactorily. The diameter of the successful one was 15½ inches. Between 1858 and 1866 he took literally hundreds of photographs of the moon with it, some of which were so good that they were capable of enlargement to three feet in diameter.

This success inspired him to make an even larger mirror—a truly notable instrument, twenty-eight inches across. He began work on it in 1869, and completed it about 1871. With this telescope he obtained his first photograph of the spectrum of a star, that of *alpha Lyræ*, on May 29, 1872. The spectroscope in this case consisted merely of a prism inserted inside the focus of the small Cassegrain mirror of his great telescope.

Henry Draper's contributions to astronomy were of the greatest importance, but from the point of view of telescope-making the most useful thing he did was to write out the methods by which his mirrors had been made, for the guidance and encouragement of other telescope-makers. His book, which he called *The Construction of a Silvered Glass Telescope and Its Use in Celestial Photography,* begins with the wise remark: "The future hopes of astronomy lie in the multitude of observers."

VI

It happened that there was a young rolling-mill foreman in the city of Pittsburgh about this time, who wanted a telescope with which he could give his wife, himself and his neighbors a view of the glories of the heavens.

He was John A. Brashear, thirty-two years old, a man who had previously looked through a telescope only once, and that a cracked glass owned by an itinerant showman. But that glimpse had definitely set him to dreaming about the skies. He used to spend his spare time gazing naked-eyed at the stars, learning the positions of the brightest of them with the aid of a star chart. He used to go out on a cinder bank overlooking the old Allegheny Observatory and wonder what the astronomers of that marvelous place were doing and seeing.

His longing for a telescope once led him to an optician named Shaw, in Pittsburgh, about purchasing an object-glass which he could mount himself. But Shaw saw only a young and uneducated mill foreman, in overalls, and remarked contemptuously that such a man would not know how to mount a telescope, and certainly would not know how to use one.

Brashear went home and consulted with his wife. Two years earlier this young couple had built a home with their own hands, working in the evening hours after Brashear had returned from the mill. Mrs. Brashear decided that if they could build a house they could certainly build a telescope.

With high courage they plunged into the new venture, little realizing the labor, disappointments and heartbreak it was to cost them. Brashear bought a coal shed from a neighbor and moved it over beside his house. Inside he installed a small steam engine, a second-hand lathe, and grinding equipment. They brought two good pieces of glass, one crown and the other flint, from the New York agents of Chance Brothers & Company, England.

When the glass came, it was in square pieces. Brashear did not know the accepted method of making the discs round, but he achieved the feat, nevertheless, by grinding off the corners on his lathe. Then began the grueling, cruel task of figuring the lenses. Every night, when Brashear came home from the mill, he found his workshop clean and ready, steam up in the boiler, and his tools laid out where he needed them. Sometimes he and his wife worked until 12 or 1 o'clock, against their better judgment. The glass took shape with most disappointing slowness.

Finally, to add to their troubles, Brashear accidentally dropped the crown lens and broke it, and a new one had to be made.

As a mill employee he had to arise at 5:30 in the morning and pass the day at the mill, returning home about 6 o'clock, unless there were breakdowns. Because it was his duty to see that the machinery was kept running, he sometimes remained on the job as long as forty-eight hours at a stretch, without rest.

These frequent interruptions, and the short time each day he was permitted to work on it, caused the figuring of the glass to progress slowly. But at length, in 1875, the lenses were ready. With the help of a friend, Brashear mounted them in a wooden tube trimmed with brass. It was a handsome job, the mounting. As for the lens itself—Brashear afterwards wrote in his autobiography that the glass was not bad, considering that he had had no previous experience. The color correction was about right—perhaps the hardest part of the task, but the lens was badly overcorrected for spherical aberration, and it was necessary to do considerable adjusting of the glass in the tube to overcome this fault.

But finally—what a night that was!—they thrust the new telescope through a window and looked for the first time at Saturn. There were the famous rings. On the moon they saw mountains, craters and shadows. Mrs. Brashear called the neighbors; dozens of persons came trooping in to have a look through John's new telescope.

The demand for glimpses through the instrument subsequently became so great that the Brashears were forced to cut a hole in the roof and turn their home into a kind of free observatory.

VII

In the spring of 1876, after a year of trying to improve his first little telescope unaided, Brashear wrote to Samuel Pierpont Langley, then director of Allegheny Observatory, to ask whether he might not bring his 5-inch object-glass to the observatory so that the great astronomer could tell him what was needed to correct it. Langley graciously replied at once, with that warm

friendliness that had made him beloved of astronomers and the public alike. Brashear was to come as soon as he wished, and by all means bring his glass with him.

So one evening, after his work at the mill was finished, Brashear wrapped his lens carefully in newspaper, and carried it to the Allegheny Observatory. Before the great man of science he unwrapped it with nervous fingers, and Langley took it in his hands and examined it.

What anxious moments! As the astronomer held up the pitiful little objective, the product of endless hours of toil and loving care in the night when other workmen were abed; as he scrutinized its polish and general makeup, intently, without offering a comment, Brashear (as he tells us in his autobiography) stood trembling before him.

At last Langley looked up from his examination. He smiled at the mill foreman who was later to become one of his closest friends. "Mr. Brashear," he said, "you have done very well!"

Then he offered some sound advice. In the first place, said Langley, very difficult types of curvature had been chosen for the lenses of the object glass; equally good results could be obtained with the simpler curves used in the finest instruments of the Clarks. In the future, if Brashear wished to continue making objectives, it might be a good idea to use the Clark curvatures.

But why go to the great trouble of making lens objectives at all, asked Langley, when it was now possible, thanks to the work of Foucault and Liebig in Europe, and Dr. Henry Draper in America, to make reflecting telescopes with a fraction of the work, which would be both bigger and less expensive, and substantially as useful, aperture for aperture, as the refractors?

But where was a mill foreman to obtain information about the grinding of such delicate curves as were necessary in the mirror of a reflector? How was he to learn about the chemical processes of silvering? The answers to such questions, Langley answered, could all be found in Dr. Draper's book, *The Construction of a Silvered Glass Telescope,* and since Langley hap-

pened to have a copy, he would lend it to the young telescope-maker of Pittsburgh for as long as it was needed.

That night as John Brashear made his way back through the streets of Pittsburgh to his home, carrying his little lens and a borrowed book, he held his future in his hands, and knew that he had found his destiny.

In subsequent weeks he read Draper's book so many times he practically committed it to memory. To his delight he found that it laid out for him specific directions for every stage of telescope-making—how to begin a mirror, how to finish and silver it, even how to mount it. Brashear and his wife determined to begin at once on the task of constructing such a telescope—one of sufficient aperture to make their first little effort seem insignificant—a reflector so large, in fact, that its aperture would almost rival that of the great refractor at the Allegheny Observatory.

The new telescope was to have a mirror 12 inches in diameter. It was to be made of the finest glass they could afford. It was to be mounted equatorially, and Brashear hoped to have it done in time to make some special studies of the planet Mars, which was then very close to the earth, and afforded a fine sight, even to the unaided eye. It was in the winter of 1877 when they set to work on the new mirror—the winter of the same year in which Dr. Asaph Hall, at the United States Naval Observatory, discovered the tiny moons of that planetary neighbor.

VIII

The glass came from the New York agents of Chance Brothers almost before Brashear had completed the necessary changes in his shop. On the same night he cut off the corners of the square glass pieces (two had been purchased for some reason, tho only one was needed), and then began the long grueling work of making a mirror, under the same circumstances as those accompanying the making of the earlier telescope. He was still working long hours in the mill; long hours to which were now added nights spent joyously in his little shop, grinding his

mirror and thinking about the glories of the skies it would soon reveal.

First the glass needed to be roughed out to the general shape of a mirror, with spherical curvature. Then came the polishing, a careful job, not to be undertaken until the workman, home from the mill, had bathed, changed his clothes, carefully cleaned away every trace of grit on his fingers, clothes, even possibly in his hair, lest one grain of dust make scratches on the disc.

When at length this stage of the work was finished, there came the careful, tedious task of bringing the spherical surface to that of a paraboloid of revolution, so that all the parallel beams of light striking the mirror would be converged to a single point.

After months of effort, this, too, was finished. The mirror now was ready for its final treatment: coating it with the shining silver that would reflect the light of the stars.

But this was a difficult business—perhaps the most difficult part of the whole matter in the days when Brashear first attempted it. The only method he knew was one that required the disc of glass to be heated. This the Brashears accomplished by placing the uncoated mirror in water, and gently warming the water until the required temperature had been reached.

And now, in went the solution. The silver began to stick to the face of the new mirror; it was working! The mirror would be finished at last!

With a snap like the report of a gun, the mirror broke in two. Brashear could never understand how the thing happened. They had taken every precaution against heating the glass too fast. They had handled it with the greatest care. The only possibility, in his opinion, was that a current of cold air, rushing into the room at the moment when they had lifted the disc partly out of the solution to observe how the silvering was coming on, had struck the brittle hot glass.

The blow was a stunning one. That night he could not sleep for turning and twisting in his bed, and thinking how, if they had done this instead of that, if they had experimented

a little more with the silvering before entrusting their precious mirror to the heat, if they had sought more advice, perhaps——

But what was done, was done. Sleepless, he stumbled next day to the mill, literally dazed by what he considered the extent of his misfortune. All his work gone: the many hours of night spent in grinding and polishing and figuring and testing. The golden time for the observation of Mars slipping away, not to return for many years. And worst of all, the sense of failure—the heartbreaking intervention of chance when success was within his grasp.

That night, when he returned to his home, his supper was steaming on the table. His working clothes for the evening were laid out, clean and ready. More, his workshop had been swept and brushed and all traces of the old mirror put out of sight. Steam was up in the little boiler. The fresh, new disc of glass (what a marvel they had thought to get two while they were at it) was lying on the workbench, waiting for the new start.

"Never mind about the old mirror," said Phoebe Brashear. "This one will be better."

It *was* a better mirror, and within two months it was polished and figured and ready for silvering. But not twice would Brashear make the same mistake. This time he experimented with silvering, using plain pieces of glass. It was difficult for him to carry on many experiments, for silver was costly, and his income meager, but within a few weeks he not only had mastered the methods he had seen printed in various places, but had devised a new and simpler one of his own.

When he had succeeded in giving his new 12-inch mirror a good coat of silver he communicated the new method—which was really a modification of one which he had read about in the *Scientific American*, to the British magazine *English Mechanics and World of Science*, which at that time was widely read by amateur telescope-makers the world over. The process immediately caught on. Forty years later Brashear stood beside the 100-inch mirror at Mt. Wilson, with Professor George

W. Ritchey, the man who ground and figured it, and remarked at the brilliance of the silver coating on that magnificent glass.

Said Ritchey: "It ought to be a good coat—it's silvered by Brashear's process."

IX

The story of John A. Brashear and his wife, and his rise from the mills of Pittsburgh to success as an instrument-maker and leader in civic life, is a warm and human tale, through which it is difficult to skip. It is the kind of saga of which Americans are fond, the sort of story of success that reaches the heart.

With his arduous, long days at the mill, and the joyous, but nevertheless wearing work at night with his telescopes, his health began to fail, and at middle age Brashear found himself at a crossroads. It was the mill or his telescopes; he could not keep both going.

Had it been a few years earlier, the outcome of this decision would have been foregone. But after completion of his first reflector, Brashear had made great progress with his telescopes. He had formed a fast friendship with Langley, and had received some work from him. Brashear already was making repairs for the instruments of the observatory and repolishing and resurfacing the prisms of rock salt used by Langley at that time for his solar observations.

When Brashear was finally confronted with a choice of future paths, he consulted with the astronomer, who took him to see William Thaw, a Pittsburgh millionaire known as the friend of science. Thaw was much impressed, and offered to set up Brashear as a telescope-maker in Pittsburgh, with a shop in the very shadow of the Allegheny Observatory. Moreover, Thaw made a most unusual proposition. If Brashear would agree never to let any piece of astronomical equipment leave his shop until it was as nearly perfect as he could make it, Thaw on his part would be willing to make up the difference between the price the work would bring and the cost of producing it.

This bargain was actually kept for several years, tho it was

not long before Brashear's name and reputation became so well known that the shop was self-supporting. From it there came a stream of notable instruments; not only great telescopes, but practically all the spectroscopic instruments in use in this country today, especially those that involved new requirements or new design. Some of the largest reflecting and refracting telescopes in the country also came from Brashear's shop, including the 30-inch reflector known as the Keeler Memorial at Allegheny Observatory, the 36-inch reflector of the University of Michigan Observatory at Ann Arbor, and the great 72-inch mirror of the Dominion Astrophysical Observatory at Victoria.

Among the important refracting telescopes produced by this concern, up until Brashear's death in 1920, were the 18-inch at Philadelphia, the 20-inch at Oakland, the 24-inch at Swarthmore and the 30-inch telescope, now doing such valiant work in stellar parallax, at Allegheny Observatory.

These instruments of course were not all products of Brashear's own hands. Early in his days as a professional maker of telescopes, Brashear allied himself with a young man named James McDowell, who had served an apprenticeship in the Pittsburgh glass mills. Both Brashear and McDowell realized the importance of joining forces with a third person, who would have the necessary theoretical training in optics. They found such a man in Professor Charles S. Hastings, of Yale University.

This triumvirate, aided and encouraged by Thaw and the succession of great men who were directors of Allegheny Observatory during Brashear's lifetime—Langley, Keeler and Schlesinger—turned out the great instruments produced by the John A. Brashear Company.

X

When Keeler became director of the Allegheny Observatory in 1892, he pointed out to Brashear and others that the growth of Pittsburgh made the old site entirely unsuitable for observation and urged that money be raised to remove the observatory

to a new and better spot. The Allegheny Observatory had played such a significant part in Brashear's life that he felt this a call not to be denied.

In a few years he succeeded in raising $300,000. The new observatory, at Riverview Park, in Pittsburgh, was dedicated on August 29, 1912. It was a fine large building, with three domes, under one of which was the famous old 13-inch refractor used by Langley, under another the 30-inch Keeler reflector made by Brashear, and under the third, not complete at the date of the dedication, was to be the fine 30-inch Thaw refractor, made by Brashear and given to the observatory by the widow of William Thaw.

Tho he was a telescope-maker always, Brashear found himself drawn more and more into civic and university events after the year 1892. In 1893 he was asked to serve as trustee of the University of Pittsburgh. In 1902 he was appointed chancellor, and served in that capacity for two years. When a suitable successor had been found, he hoped it would be possible for him to return to the work he loved at his telescope shop, but he was again disappointed. He had become too great a civic figure. In the subsequent years he became leader of all sorts of projects, charitable, educational, scientific, literary and musical.

He received many honors. Doctorates were conferred upon him by the Universities of Pittsburgh, Princeton, Wooster, Washington and Jefferson, and Stevens. He held membership in a number of scientific societies, local and national. When, in 1915, the governors of the various States were asked to delegate their most eminent citizens to the Panama-Pacific Exposition in San Francisco, the governor of Pennsylvania unhesitatingly nominated Brashear.

On his seventy-fifth birthday the city of Pittsburgh honored him at a testimonial dinner attended by thousands of persons, and one of the features of the occasion was the announcement of a fund which had been raised to continue, in his name, the series of lectures on astronomy he had given regularly and without payment for many years.

He died in 1920, four years after the completion of a long

tour in the western part of the United States and the Orient, in the company of Ambrose Swasey, of Warner & Swasey, one of his closest friends. In the opinion of some persons, his death was hastened by that journey, but it was one he very much wanted to take; it was on that occasion that he stood with another great American telescope-maker, Professor George W. Ritchey, beside the 100-inch telescope at Mt. Wilson.

When the memorial telescope to Keeler was finished in 1906, the astronomer's ashes were removed from California and placed in the beautiful crypt at the base of the telescope. In the same crypt, mingled together, the ashes of Brashear and his wife now lie. The inscription on the tablet was chosen by Brashear himself, from an anonymous poem called "The Astronomer":

"We have Loved the Stars too Fondly
to be Fearful of the Night."

XI

James McDowell, who had become the husband of Brashear's foster-daughter, Effie, had carried on the wheelhorse work of the telescope business during the latter years of Brashear's attention to civic affairs. He was a telescope-maker of the finest skill.

But he, too, was getting old, and felt the need of a younger man to take care of business details and run the establishment. It happened that among Brashear's firmest friends were the instrument-maker Gottlieb L. Fecker, and his son, J. W. Fecker. Gottlieb was the man who, as a final triumph in a life devoted to the production of fine instruments, brought to a state of near-perfection the marvelous Warner & Swasey 40-inch dividing machine, an apparatus used to mark the tiny lines for degrees, minutes and seconds on graduated circles of telescopes and other astronomical instruments.

The talent of J. W. Fecker exceeded even that of his father. In 1923 McDowell made a journey to Cleveland, where the

younger Fecker was making instruments under his own name, and proposed that he join forces with the Brashear interests at Pittsburgh and carry on the business there. Before these arrangements could be finished, McDowell died, but the trustees of the estate completed them.

One of the first important big mirrors made by J. W. Fecker at Pittsburgh was the 69-inch reflector of Perkins Observatory, using the first large glass disc ever cast in this country. It was a notable achievement, one that proves the establishment fit to bear the subtitle which appears on its letterhead: "Successor to John A. Brashear and J. B. McDowell."

XII

"Those who seek to find an explanation for the remarkable activity in observational work in this country that this generation of astronomers has witnessed, will undoubtedly conclude that three commercial organizations have played a large part in this development: the Clarks in Cambridgeport and the Brashears in Pittsburgh, so far as optical matters are concerned, together with Warner & Swasey Company of Cleveland, on the mechanical side."

So wrote Dr. Frank Schlesinger, director of Yale Observatory, in an article for *Popular Astronomy* outlining the career of Brashear. Without question he gave credit where it was due. These three commercial concerns have done more to make America the world center for fine astronomical instruments, and to develop those instruments to their present state of usefulness, than any other single factor in modern astronomy.

Let nobody think that the mechanical side of modern telescopes is the less important part. Upon the mounting depends the beauty, gracefulness and above all, the usefulness of the instrument. The possible number of variations of design is almost infinite; yet every successful mounting must have the qualities of rigidity, balance and easy, vibrationless movement. The perfect telescope, tho it weigh hundreds of tons, must be so nicely poised on its polar axis that a small clock can drive

it; its graduated circles must be so finely divided and so well mounted that the tiniest invisible object in the heavens can be found in the field of the instrument by proper setting of the circles.

In a sense, it is a problem of how to construct an apparatus as large and heavy as a locomotive, yet as delicately adjusted and easy to operate as the finest watch.

This problem first attracted the attention of Worcester Reed Warner during his boyhood on a New England farm. His mother, who was interested in astronomy, encouraged him. While still in his teens he built his first successful telescope out of some old machine parts.

Later, when he was apprenticed to a machine shop at Exeter, New Hampshire, he met another young man of his age and tastes named Ambrose Swasey. They struck up a firm friendship, and both resolved to save their money until they had enough to go into business for themselves in the West. Completing their apprenticeship, they found employment together in the machine shops of Pratt & Whitney at Hartford, Connecticut. Ten years later, deciding that they had at last saved enough for the great plunge, they left their jobs and moved to Chicago to open their first shop.

The venture proved a failure, chiefly because in 1880 it was difficult to get skilled workmen so far from the large industrial centers of the East. Compromising, they moved to Cleveland, and tried again. This time they were joined by four friends who had formerly worked with them at Hartford.

Almost miraculously the shop began to succeed. The first order was for twelve hand lathes, which were executed with such expertness that new orders for various kinds of machines poured in. Then Warner remembered that his major reason for wanting a machine shop of his own was to build telescopes. In the first year he found time to complete a small equatorial refractor of 9½ inches aperture.

The first of the great instruments mounted by this firm was the 36-inch Clark refractor of the Lick Observatory at Mt. Hamilton. It was set up during the winter of 1886-87, only five

years after the completion of their first small telescope. The mounting attracted so much praise that Warner & Swasey were commissioned to make one of similar design for the 26-inch telescope of the United States Naval Observatory at Washington, for which the objective and original mounting had been made by the Clarks. They later designed and constructed the mounting for the 40-inch Clark telescope, as well as the 90-foot dome and 75-foot elevating floor, of the Yerkes Observatory.

Among the other large telescopes mounted by Warner & Swasey are the 72-inch instrument of the Dominion Astrophysical Observatory at Victoria, B. C., the 69-inch telescope at Perkins Observatory, and the 60-inch reflector of the Observatorio Astronomica at Córdoba, Argentina. The 82-inch telescope of the McDonald Observatory was constructed, optical parts and all, by this company under the direction of E. P. Burrell, director of engineering.

Worcester Warner died in Germany in 1929. At his country home, Hillholm, in Tarrytown, N. Y., he had for many years maintained one of the finest small private observatories in the country, and had in it an 8-inch equatorial telescope with an object-glass by Brashear. That fine little telescope, a jewel both as to optical parts and mounting, has now been presented to the American Museum of Natural History, New York, by Mrs. Warner. It will be mounted in a dome atop one of the highest parts of the museum building, where visitors may use it to look at the stars. It is to become a permanent part of the museum's fine collection of astronomical instruments.

Ambrose Swasey, who survived his partner eight years, had reaped the honors due an unusually fruitful life. In 1900 he received the decoration of Chevalier of the Legion of Honor from the French Government. The Case School of Applied Science at Cleveland awarded him the honorary degree of Doctor of Engineering. He was similarly honored by Denison University, Granville, Ohio. He was a charter member and past president of the American Society of Mechanical Engineers,

past president of the Cleveland Engineering Society, and a member of the National Research Council.

XIII

Now for the story of another American telescope-maker—the scientist and astronomer who figured some of the largest mirrors in the world, including the 100-inch Hooker telescope and the 60-inch reflector of Mt. Wilson, and who primarily was also responsible for the development of at least two new types—the sun-telescopes of Mt. Wilson, and the new photographic wide-angle reflectors such as that constructed for the United States Naval Observatory.

He was George Willis Ritchey, a man of such quiet and unassuming personality that, though his name is linked with some of the largest telescopes in the world, he was almost totally unknown outside the small world of technical astronomy. His work was such as to rival the skill of Herschel, yet no kings honored him. In his last years he was content to live quietly in his home in Azusa, California, while the greatest astronomers studied the universe with mirrors fashioned by his hands.

He was born on December 31, 1864, in the little town of Tuppers Plains, Ohio. His father, an amateur astronomer, first stirred his interest in telescopes. As a young boy, Ritchey decided that he would become a professional astronomer.

He made his first reflecting telescope, a mirror nine inches in diameter, while attending Cincinnati University. Upon graduation he moved to Chicago, taking his small instrument with him, and when he was twenty-four years old he set up an astrographic laboratory in his Chicago home, complete with machinery and power drive. For eight years he worked there in his spare time, meanwhile supporting himself by teaching at the Chicago Manual Training School.

In his Chicago laboratory he developed many of the optical, mechanical and photographic refinements which he used later at Yerkes and Mt. Wilson Observatories. He also acquired there

the remarkable skill with mirrors that attracted the attention of Dr. George Ellery Hale.

In 1896, when the Yerkes Observatory of the University of Chicago was being built, Dr. Hale invited him to join the staff as optician. Ritchey accepted, bringing along with him a 24-inch mirror of 8-foot focus he had made in his laboratory. One of his first achievements at Yerkes was the mounting of this mirror. With it he later made a series of important photographs of star clusters, nebulæ and spirals, and discovered the expanding nebulosity around *Nova Persei.*

A well-known picture taken with this remarkable little reflector is the one of the Great Nebula in Andromeda often reproduced in books on astronomy, and shown in Plate 18. A four-hour exposure was necessary to obtain this photograph.

At Yerkes, Ritchey became successively superintendent of instrument design and construction at the observatory, instructor of practical astronomy at the University of Chicago, and finally assistant professor. Meanwhile he was busy in the optical shop, where he designed and made most of the auxiliary equipment needed for the great refractor.

Now the 40-inch refractor had been made for visual use, and hence was useless for photography. But Ritchey found a way to adapt it, with the use of color filters and specially sensitized plates, and made the first series of sharp photographs with it, including pictures of globular clusters and the moon. A photograph of part of the moon, showing the remarkable magnification possible with this instrument without loss of detail, is reproduced in Plate 19. It may be compared with a photograph much less magnified, taken with the 100-inch Hooker telescope, which appears on the same plate.

When Dr. Hale laid the foundations for the great observatory at Mt. Wilson, one of his first considerations was the establishment of a well-directed optical shop, so he invited Ritchey to take charge of it. As head of the shop, the telescope-maker began to turn out the series of instruments which rapidly brought the new observatory to world attention.

The 60-inch mirror he had carried to the stage of polishing

and figuring at Yerkes. At Mt. Wilson he finished and mounted it, in the useful fork-type modified Cassegrain mount that has made this telescope one of the most useful in the world. The dome and building which house the 60-inch are also of Professor Ritchey's design. With this instrument he made photographs which were among the first to prove that the larger spiral nebulæ are other stellar systems similar to our own. In a sense the photographs taken by Ritchey with the 60-inch reflector inaugurated the "new astronomy" of the regions outside our galaxy.

Equally important, they aided Ritchey and Dr. Hale in bringing the question of larger telescopes to the attention of Mr. Hooker. When money was raised for the 100-inch reflector, it became Ritchey's job to make it and design the mounting. Aided by assistants at the shop he worked nearly three years on the all-important designs, and when the disc was at length received from the St. Gobain Glass Works it was Ritchey, with two assistants whom he had trained, who ground, polished and figured it. Ritchey also made all the smaller optical mirrors for the telescope.

The great mirror and its parts were finished in 1917. At the request of the United States Government, Ritchey then temporarily left off his life-work, and in a large optical shop built for the United States Ordnance Department at Pasadena, he trained more than 100 young men and women in making optical parts for telescopic gunsights. When the war ended, this work ceased, and he built a private laboratory in California. There he developed many of his later inventions for the construction and operation of photographic reflecting telescopes.

These include the famous Ritchey ventilated cellular mirrors, built up of plates and interior ribs of glass or Pyrex, with intermediate hollow spaces for lightness and temperature control; also the short, compact type of photographic telescope now known as the Ritchey-Chrétien.

Both of these novel ideas attracted much attention, especially in France. In 1923 he was invited to visit that country by the National Observatory at Paris. He established an astrographic laboratory at the observatory, and working with the Optical Institute of Paris and the St. Gobain Glass Works (successors to the original makers of the 100-inch disc), he refined the exquisite curvatures of the Ritchey-Chrétien telescope, and built the first of them, a 20-inch, for the private observatory of the Duc de Gramont at Vallières.

In the seven years spent in France, Ritchey also made his first large cellular mirror, completing one 60 inches in diameter.

Ritchey returned to America in 1931, at the call of the United States Naval Observatory, and immediately began the construction of his 40-inch Ritchey-Chrétien photographic telescope, which he completed about 1936, and which he considered one of his finest accomplishments.

At the time of completion of this instrument Ritchey was seventy-two years old. He retired to Azusa, California, where he died nine years later, in 1945.

Chapter XVI

NEW INSTRUMENTS—THE SCHMIDT CAMERA AND THE CORONAGRAPH

I

ON September 14, 1940, there was an interesting little ceremony at the Oak Ridge Station of Harvard Observatory, where members of the American Astronomical Association had journeyed enthusiastically to view a new kind of telescope.

It was the 24-inch Harvard *Schmidt camera*—a type which had been invented only ten years previously by a German optician, Bernhard Schmidt, associate of the Hamburg Observatory at Bergedorf. Schmidt's instrument, called a camera because it can not be used for any except photographic work, was hailed by members of the association as one of the most significant telescope developments in many decades.

And well it may have been. For with a simple combination of two optical parts: a spherically figured mirror and a thin lens of glass, the German had succeeded in overcoming at least two of the difficulties connected with ordinary reflecting telescopes. In addition he had increased the speed and widened the field of view. His cameras have opened up whole new fields of photographic astronomy, and have freed large-scale explorers of the skies from the hampering problems which the conventional reflectors always brought.

For when Professor Ritchey developed his Ritchey-Chrétien type of photographic telescope for the U. S. Naval Observatory and elsewhere, he was simply expressing in his own way the

dissatisfaction astronomers had begun to feel toward the limitations of the reflecting telescope when used as a camera.

In light-gathering power the large reflector is of course unsurpassed. It also has great flexibility, for the observer may use it either at the prime focus, at the Newtonian focus, or at the Cassegrain or coudé foci. But for these advantages something has to be paid. In the case of the usual reflector the payment is at least twofold; since the familiar type of reflecting telescope exhibits two optical defects which in photographic work become increasingly serious with size. These defects are (1) a relatively small field, and (2) a distorted image around the outer portion of the field.

Most noticeable of the distortions is the image defect called *coma*. Now coma is the tendency of star images at the edge of the photographic plate to become elongated slightly, so that they resemble teardrops rather than sharp, round perfect discs. Coma is caused by the fact that, though the paraboloidal mirror is able to focus parallel rays to a point, and hence produce a perfect image when the rays fall directly along its optical axis, it cannot similarly focus to a point the pencils of rays that strike it *obliquely*. These oblique rays, such as come from a star at the edge of the field, are slightly distorted, the amount of distortion being relative to the angle which the incoming rays make with the true optical axis.

If this seems a bit complicated, it adds up to the fact that in any parabolic reflecting telescope, only the star images at the exact center of the field will be perfect. In the zones around the center they become increasingly enlarged, and farther out they may be pulled into the shape of a pear, with the small end pointing in. Toward the edges of the field this effect may be so bad as to make the images useless.

The other optical defect of reflecting telescopes is astigmatism, which in practice is usually not as objectionable as coma, because it makes its appearance further off the optical axis; hence the defect of coma masks it. If coma can be overcome, however, astigmatism must then be dealt with. This defect has the effect of producing star images near the edges of the

field which are shaped like lines or ovals instead of well-focused small discs.

II

Neither of these defects was particularly serious, of course, so long as astronomy consisted largely of visual observing. The observer can pay attention only to a small part of the field at a time in any case. But the photographic plate can give equal attention to every image that falls on it, and the bad images are photographed along with the good ones. The smallness of the reflector's field likewise is of no great disadvantage to visual astronomy, but it hampers photographic astronomy. The camera plate could accomplish more than the limitations of the instrument permit it to do.

One of the earliest suggestions for overcoming the problems of the parabolic reflector was made about 1905 by the noted German astronomer Konrad Schwarzschild.

Schwarzschild's suggestion was that coma could be eliminated by adding a second mirror to the system, the mirrors being so shaped that the curvature of the second would exactly correct the distortions produced by the first. Such a telescope would be a photographic instrument only. It could have but one focus, and might be used only as a unit, giving up the flexibility of the ordinary reflector in order to gain a wider field of view and freedom from coma.

The type of camera telescope suggested by Schwarzschild has been successfully constructed, and there are at least two of them in this country: a 24-inch of 80 inches focal length at the University of Indiana, and a 12-inch of 36 inches focal length at Brown University.

The Schwarzschild camera employs a second mirror in front of the main mirror, and brings the image to a focus between the two mirrors. The photographic plate must, in consequence, be inserted into the tube facing outward, toward the sky. This makes it necessary to place a "sky fog baffle" of some length on the end of the already rather long tube of the camera to

keep stray side light from getting into the instrument and fogging the plate.

In order to permit the use of ordinary flat photographic

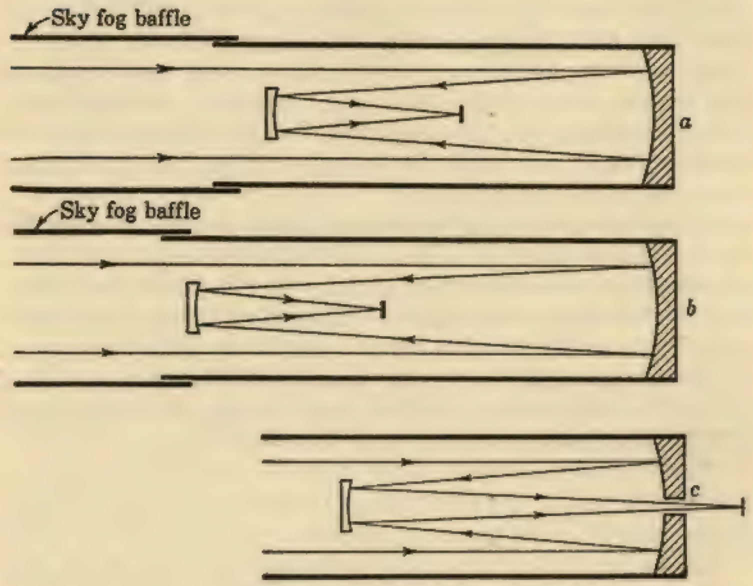


Fig. 46

The three principal types of two-mirror photographic telescopes: (a), the Schwarzschild camera. (b), the Couder camera. (c), the Ritchey-Chrétien.

plates, the Schwarzschild camera is designed in such a way as to bring the image to a flat focus. But this is done at the expense of retaining the defect of astigmatism. This, plus the long tube and fog baffle which make observatory construction difficult, have prevented the Schwarzschild instrument from becoming especially popular with astronomers, despite its obvious advantages.

The French scientist Couder also investigated the possibilities of the two-mirror photographic reflector, and some years

ago designed one that overcomes both coma and astigmatism. Like Schwarzschild's camera, the Couder camera brings the image to focus between the mirrors, and consequently requires a sky fog baffle. The tube, as in the Schwarzschild, is long. But what makes the Couder camera especially difficult is the fact that astigmatism is overcome by introducing a curved focal surface, requiring curved plates. This would not be too severe, but coupled with the long tube, the baffle and other problems, it has kept the Couder camera, like the Schwarzschild, primarily in the class of interesting but not very acceptable instruments.

The Ritchey-Chrétien telescope belongs to this same family of two-mirror cameras. It has a curved focal surface, and consequently requires the use of slightly curved plates. But it has a great advantage over both the other types in that the second mirror passes the image through a hole in the primary mirror, as in a Cassegrain reflecting telescope. The image is thus formed *behind* the main mirror, and the tube of the telescope can be considerably shorter than the focal length.

The Ritchey-Chrétien is best suited for relatively long focal ratios—the one at the U. S. Naval Observatory having a focal length nearly seven times its aperture. This is rather slow for a camera for, as we have seen, the longer the focal length, the larger the image. For visual work a large image may be an advantage, but in photography what is usually wanted is speed—that is, high concentration of light on the image at the photographic plate. This is best obtained by a short focal ratio. A good camera usually has a focal ratio only about three times the diameter of the aperture—a ratio usually written f/3.

III

Thus, up until 1930, though there had been some interesting experiments in the direction of better photographic telescopes, no really effective type had appeared; nothing at least that

seemed likely to challenge the supremacy of the conventional reflector.

Then came Schmidt's new instrument at Bergedorf: a telescopic camera that overcomes in one design the image defects of coma and astigmatism; has a reasonably short tube without the need for a sky fog baffle, provides a fast focal ratio and a large field of view, and is relatively simple to make.

Schmidt chose neither the reflecting nor the refracting telescope for his model, but produced instead a combination of the two. The Schmidt camera contains two optical parts: a mirror and a lens. The mirror is placed at the rear of the tube as in conventional reflectors, and the lens is at the forward end of the tube, so that the light must pass through it on the way to the reflector. The image is brought to focus inside the telescope between the mirror and the lens, but the photographic plate faces toward the rear, hence is not troubled by sky fog.

The mirror of the Schmidt camera is quite easy to produce, for it has a spherical figure instead of the paraboloid. As we have seen, the spherical figure is one of the preliminary phases in the production of a parabolic mirror, and is obtained without too much difficulty. In constructing an ordinary reflecting telescope, the maker must first produce a spherical mirror, then overdeepen it into a paraboloid. When making a Schmidt, he can stop at the spherical stage.

The other part of the Schmidt camera, the lens—usually called the *correcting plate*—is much more difficult. For it is not a simple lens of spherical curvature like those used in refracting telescopes, but must be specially figured. Moreover, it is very thin. The figure—generally a hump in the middle, is so slight that it usually cannot be detected by the unaided eye.

The advantage of the Schmidt camera lies in the fact that the rays of parallel light falling on a spherical mirror *from any forward angle* will be brought to a focus, and hence a spherical mirror does not suffer from coma. The focal point of a spherical mirror will not be the same for all rays, however, and such a mirror, uncorrected, would be subject to severe spherical aberration. It is the function of the correcting plate

in the Schmidt camera to overcome the spherical aberration; hence the necessity for very precise figuring.

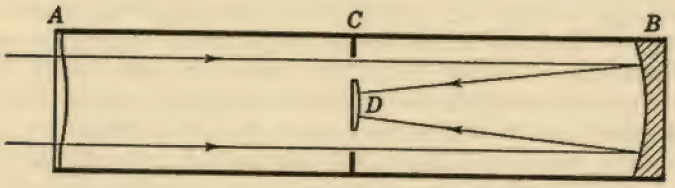


FIG. 47

The Schmidt camera. Light enters through the correcting plate A (curvature much exaggerated in the drawing), passes on to the spherically figured mirror B, and is brought to focus at D, where a slightly curved photographic plate is used to catch the image. C is a diaphragm to control the size of the aperture.

In construction, the correcting plate of the camera is placed at the *center of curvature* of the mirror. The light rays pass through it on their way to the mirror, and are caused to fall on it in such a way that the spherical mirror acts to bring the whole image to focus in a single surface, as would a parabolic reflector. The arrangement permits very short focal ratios. Schmidt cameras now in operation range from about f/3, which is short for a reflector, down to f/1 and less, making these cameras very fast indeed.

The Schmidt has two defects that keep it from being the perfect instrument. In the first place, the tube must be about twice as long as that needed in a conventional reflector of the same focal length. More serious, because of the inconvenience it causes, the focal surface is curved to overcome astigmatism, and thus requires the use of curved plates.

Several ingenious schemes have been proposed to overcome the latter difficulty, some mechanical and some optical. One of the most promising ideas is the introduction of an optical "field flattener"—a plano-convex lens inserted in the instrument just in front of the photographic plate. This can do its work, of course, only at the expense of some lost light, but

possibly offers a practical way of dealing with the curved plate difficulty in the immensely useful Schmidt.

IV

The Harvard Schmidt camera viewed by the members of the American Astronomical Association on the occasion of their sixty-fourth annual meeting in 1940 was the first of the large instruments of this type to be constructed.

Known as the Jewett Memorial Telescope for Professor James R. Jewett of Harvard (whose substantial gift made it possible), and Mrs. Jewett, this camera has a 33-inch mirror and a 24-inch correcting plate, and in 1940 was the largest Schmidt in operation. It has a field ranging from 10 to 100 square degrees, depending on the equipment used with it (the useful field of an ordinary reflector is usually less than one square degree). It was especially designed for use in the Harvard surveys of the distribution of galaxies and stars, where large coverage and high speed are important.

An unusual feature of this telescope is the way it is mounted. With the exception of the polar axis and counterweights, the mountings are of Dowmetal, a strong magnesium alloy about one-third lighter than aluminum. The Jewett telescope is the first major astronomical instrument to employ this material.

The building, constructed especially for the Jewett Schmidt camera, is twelve-sided, and is insulated with homosote. A unique feature is that the entire structure revolves, instead of the dome only as is the usual practice.

A Schmidt camera of somewhat smaller size—an 18-inch—had the distinction of being the first major instrument to commence work at the new observatory atop Mt. Palomar. This observatory, constructed primarily to house the 200-inch reflecting telescope and its appurtenances, began operation shortly before the Second World War, when the finishing of the 200-inch mirror had to be postponed.

The 18-inch Schmidt has a mirror 26 inches in diameter, and is therefore a much larger instrument than the relatively small

correcting plate might indicate. Its success caused the observatory to order an even larger Schmidt, which was begun in 1940. The second Mt. Palomar Schmidt camera has a 72-inch mirror, and a correcting plate 48 inches across. When finished it will outrank in size all but the Schmidt being constructed by Fecker for the Boyden Station of Harvard Observatory at Bloemfontein, South Africa; an instrument which will have a 60-inch mirror and a correcting plate of equal size.

Schmidt cameras of 10 inches or more aperture, in operation by the end of 1940 or under construction, include the following, as tabulated by Professor Charles Smiley, director of Ladd Observatory, for *Telescopes and Accessories*, by George Z. Dimitroff and James G. Baker (1945):

Observatory or individual	*focal ratio*	*Diam. plate-inches*	*Diam. mirror-inches*
Harvard	2.5	60	60
Palomar	2.5	48	72
Tonanzintla	3.5	26	31
Case School	3.5	24	36
Harvard	3.5	24	33
Flagstaff	3.5	24	31
Mellish, Escondido	2.25	20	20
Palomar	2.0	18	26
M. R. Schottland	2.7	16	24.75
Bergedorf	1.74	14	17
Hildom, Los Angeles	2.5	12	16
Cook Observatory	2.5	10	15

In addition to these, some thirty smaller Schmidts were also in use by 1940 in various parts of the country; an amazing record for an instrument which had been invented only ten years previously.

V

The success of the Schmidt of course spurred other investigators to make a search for further improvements in the photographic telescope.

One proposed improvement—known as the Wright camera

after F. B. Wright, who developed it—has undergone some development. A Wright camera is in operation at Lick Observatory, another at Harvard Observatory and a third at the observatory of C. E. Wells at Roseville, Calif.

Wright arrived at his design after a study of all possible positions of the correcting plate with respect to the primary mirror of the Schmidt. He found that it is theoretically possible to figure the correcting plate so as to produce a camera without coma or spherical aberration for every position along the axis of the instrument. The three Wright cameras now operating have the correcting plate *behind* the focal point of the mirror. This provides easy access to the plateholder, since the image can be readily reflected sidewise out of the tube, as in the case of a Newtonian reflector. The focal surface of the Wright camera is flat, permitting the use of ordinary plates. But it has astigmatism.

Other possible variations of the photographic camera idea, combining two mirrors or a combination of mirrors and lens, have been proposed by D. D. Maksutov of the State Optical Institute at Moscow, by E. H. Linfoot, in England, and especially by George Z. Dimitroff and James G. Baker, of Harvard Observatory. Dimitroff and Baker, in their book *Telescopes and Accessories,* suggest three new types of camera using a correcting plate and two mirrors. With these optical parts, suitably figured, they have derived instruments which appear to provide a flat focal plane, freedom from coma and astigmatism, a field comparable in size to the Schmidt.

No one can say, of course, whether we are yet at the end of improvement of the photographic telescope, but it is certain that with the Schmidt and its later forms, both actual and proposed, great new possibilities in photographic astronomy have been opened, the results of which cannot now be imagined.

The magazine *Science* recently declared the Jewett Schmidt camera at Harvard Observatory to be "one of the three or four most important telescopes of the twenty-five in regular use at the Harvard Observatory, and—in some ways—the most

important. It will greatly extend the survey of the external galaxies in the northern hemisphere and it is believed that perhaps a million galaxies will be within its range."

VI

There is another new type of instrument at work in this country which brings us much closer to home, for it gives us daily news of goings-on at the surface and in the corona of our own sun—and therefore discloses something of what may be daily occurring in every star.

This instrument is the coronagraph, first developed successfully by the French astrophysicist Bernard Lyot (see pages 192-193) about 1930. A larger, improved and more powerful instrument was completed by Lyot three or four years later, and was used by him with great success in his observatory at Pic du Midi in the Pyrenees. In 1938 he reported on its work before the International Astronomical Union meeting at Stockholm, and several observatories here and abroad began figuring on making coronagraphs for their own use.

The value of the coronagraph, of course, is that it enables astronomers to study the sun's corona, prominences and other surface phenomena at will, without awaiting an eclipse. While much of the solar phenomena are also disclosed by other instruments, the Lyot coronagraph does it with such simplicity and readiness that continuous studies of the sun throughout the daylight hours are possible, either visually or by photography. Moreover, motion pictures can also be made, which bring the solar phenomena to life again later for study at leisure.

Several Lyot-type coronagraphs are now in existence. As long ago as 1932 Drs. Pettit and Slocum of Mt. Wilson Observatory constructed one in this country, but it was used for photographic studies of the prominences rather than research on the corona. About 1939 Dr. Max Waldmeier, who had worked with Lyot in the Pyrenees, constructed a Lyot-type coronagraph and installed it in an observatory at Arosa, Switzerland, where it is now in use.

The first large American Lyot-type coronagraph was finished about 1940. It was constructed under the supervision of Dr. Donald H. Menzel, of Harvard Observatory, and was promptly put to use in a closely guarded solar observatory high in the Rocky Mountains at Fremont Pass, near Climax, Colorado. There it took part during the Second World War in research connected with the Allied military programs throughout the world. For news of the sun's behavior is of major importance in connection with radio transmission, upon which all modern war operations depend.

The Menzel-Lyot coronagraph is 5 inches in diameter, 96 inches in focal length. It is photoelectrically aimed by means of an auxiliary instrument parallel with the main optical system, utilizing a lens of the same focal length.

Only recently have details of the Fremont Pass instrument and its work been made public. Enough has been disclosed to indicate that a new period in solar research may be about to open. What the eye and camera see through the coronagraph, combined with present knowledge of the atomic power transformations going on in the sun, at last is enabling astronomers to begin constructing sound theories of the corona, the prominences and the innumerable small spikes and "spicules" which dance upon the solar surface, and which can be viewed at will through the coronagraph on any clear day.

The sun is known, of course, to be an enormous machine for the release of atomic power, transforming its hydrogen into helium through a carbon-nitrogen cycle which is steadily increasing in intensity and will continue to do so until the hydrogen is all consumed: a time estimated at ten billion years. Thus the astronomers who view the sun through the coronagraph are really witnessing a spectacle, on giant scale, like that over Hiroshima and Nagasaki when the comparatively puny man-made atomic bombs were exploded there in the summer of 1945.

The principal resident astronomer at the Fremont Pass station is Dr. Walter Orr Robert, the superintendent. The

location has an elevation of 11,532 feet, and Fremont Pass station is the highest permanent observatory in the world. In addition to the coronagraph, the observatory's instruments include a telescope with special color filters and an automatic motion-picture camera.

In the service of these instruments Dr. Roberts and his wife lead an heroic and at times almost hermit-like existence. Snow falls at Fremont Pass at virtually any time of year, and becomes so immensely deep in the wintertime the roof of the observatory has been given the shape of a steep cone to help shed the weight of it. Winter temperatures fall to 32 degrees below zero in the unheated observatory. Nevertheless, the astronomers there have photographed the sun every ten minutes or oftener on every clear day, and have studied the effects of solar activities on radio reception and the weather, compiling data which was of signal usefulness during the war, and which has many practical peacetime applications as well.

The Fremont Pass observatory has been operated since its founding as a station of the Harvard College Observatory. Plans are now formed under which Harvard Observatory will join efforts with the University of Colorado in establishing a much expanded high altitude observatory near the present site. The new observatory will incorporate the facilities of the Fremont Pass observatory, and also will provide equipment for the pursuit of cosmic-ray research and several other types of scientific studies for which high altitude is of importance.

Chapter XVII

THE 200-INCH AT MT. PALOMAR—THE WORLD'S GREATEST TELESCOPE ADVENTURE

I

ONE day in 1927, in his pleasant study in Pasadena, Dr. George Ellery Hale began to prepare the manuscript for a slender, mild-mannered little book, *Signals from the Stars* (Scribner's). The theme of the book was Hale's opinion that telescopes, for all their size, weren't large enough. He urged bigger ones—even up to 200 or 300 inches aperture; crying, as did the Arabian astronomer El Karakat seven centuries before him: "How minute are our instruments in comparison with the celestial universe!"

From that little volume sprang the world's greatest telescope adventure. The first sections of the book appeared as articles in *Harper's Magazine, Scribner's,* and *Popular Astronomy.* The ink was hardly dry before Hale's larger telescope began to materialize. Prompted by his suggestion, the International Education Board, now part of the Rockefeller Foundation, offered the California Institute of Technology enough money to construct the most complete astrophysical laboratory in existence, including a telescope of 200 inches aperture.

It was no small undertaking: the new telescope and its equipment would cost close to $6,000,000. It would require twelve years or more to construct, counting the preliminary research and preparation. It would be a scientific and engineering problem of an order to challenge the world's foremost authorities.

And if successful, what an achievement! A telescope larger by twice than any other in existence, catching four times as

much light as the 100-inch at Mt. Wilson. A telescope capable of concentrating on a small brilliant image 800,000 times as much light as is captured by the human eye. And while that poor, puny instrument with which man is naturally endowed is capable of seeing a few thousand very bright stars, this creation of his mechanical skill and optical genius would be able to discern 6,000 million of them; enlarging the volume of the present visible universe some thirty times, reaching out into space the magnificent, terrifying distance of 1,200,000,000 light years!

II

An amount of preparatory work equal to that of planning a dam or designing a ship was in prospect. The first step was the organization of an Observatory Council, to consider the problems of design, construction, location and minor and major detail. Befitting the magnitude of the project, this Council included some of the country's foremost astronomers, executives and engineers. Among them were the noted physicist, Dr. Robert A. Millikan, director of the Norman Bridge Laboratory of Physics and chairman of the executive council of the California Institute of Technology; Dr. Arthur A. Noyes, director of the Gates Chemical Laboratory of the California Institute of Technology; Henry M. Robinson, California lawyer and banker, and Dr. Hale. Others added later included Dr. Max Mason, former president of the Rockefeller Foundation, who became vice-chairman in 1936. Chosen as executive officer was Dr. John A. Anderson, of the staff of Mt. Wilson Observatory, known for his skill in devising optical and seismological instruments, and for his astronomical work.

These men did not undertake the important problem of designing the telescope alone. They called to their aid an advisory committee headed by Dr. Walter S. Adams, director of Mt. Wilson Observatory. The committee in turn sought the advice of virtually every well-known and experienced telescope-builder and astronomer in this country and abroad. Tho the experts of Mt. Wilson Observatory already had more than twenty-five

years of experience to their credit, they called upon such skilled designers as Russell W. Porter, of Springfield, Vermont, and later took him to aid in the work; Dr. Ambrose Swasey and E. P. Burrell, president and chief engineer, respectively, of Warner & Swasey; and Gano Dunn and S. R. Jones of the J. G. White Engineering Corporation. European authorities were also consulted, including Sir Herbert Jackson, director of the British Scientific Instrument Research Association, and the late Sir Charles Parsons, son of Lord Rosse, who was not only a distinguished engineer, but had founded one of the most successful optical-glass and telescope works in England.

As if this galaxy of experts was not enough, the Council called upon scores of other authorities in specialized lines. One of the gravest problems, for example, was whether a 200-inch telescope would prove useful in proportion to its aperture and cost. This factor in any new instrument is always a gamble, for, while seeing conditions in a given locality may be excellent for instruments of moderate size, an increase may prove disastrous because of the greater effect of air ripples.

This problem was taken to the late Dr. F. G. Pease, of Mt. Wilson Observatory, and with the famous Michelson stellar interferometer attached to the upper part of the 100-inch telescope, Dr. Pease made tests for varying apertures at that location. These amply demonstrated the safety of building a 200-inch instrument. When the sliding mirrors of the interferometer are fully opened out, they represent an aperture of 20 feet. Dr. Pease found that the seeing would be satisfactory in the vicinity of Mt. Wilson, even with a telescope of this entire diameter.

Dr. Hale's first surmise—that if a larger telescope were made it would be entirely practical—was thus confirmed.

III

It was recognized that the 200-inch telescope involved three major problems: (1) the casting and figuring of the huge optical parts, (2) the design and construction of a mounting

sufficiently sensitive to swing these mirrors properly across the sky, and (3) the choice of a suitable location.

The problem of the mirror was first to be considered, for naturally there would be no telescope unless the principal optical part could be produced. And this problem was no easy one. A suitable disc must possess hardness, strength, homogeneity; must be capable of taking and holding a good figure and polish, and must show small expansion or contraction under changes of temperature. All these characteristics are important even in the smallest reflecting telescopes. As mirrors become giants, faults too small to be troublesome in lesser instruments assume the greatest practical significance. A high index of expansion, for example, may be only an annoyance in a 12-inch telescope, but in one of 200 inches even a small change of figure with temperature fluctuations may render the telescope useless for hours, may alter its figure more or less permanently, or may even crack the glass.

When the figure must be true to about two-millionths of an inch, variations in curvature from any cause are serious. If the glass contains strains or lacks homogeneity, one part may expand or contract faster than another, ruining the figure. Again, the curvature may become permanently warped because of the slow adjustment of stresses within a badly made disc.

Considering these matters, the designers of the 200-inch telescope began a search for the most suitable material. Several types of glass were considered, of course; but this did not end the matter. Investigated also were speculum metal, patented hard alloys such as Invar and Stellite, and numerous others. Natural glasses such as obsidian were subjected to experiment; also large naturally occurring crystals. These were all found to have obvious faults which excluded them. Thought was given to the construction of a cellular mirror, such as that suggested by Professor George W. Ritchey, but the difficulties were considered too great. The same objection precluded making a mirror from many pieces of glass cemented or fused together, or a mirror consisting of many hundreds of small mirrors mounted together on a rigid base.

The choice finally came down to two materials: fused quartz, which has the lowest index of expansion of any of the glasses, and special low-expansion glass of the type known as borosilicate. For a time it appeared that a feasible way would be found to make a mirror of pure fused quartz. Dr. Elihu Thomson and his associate, A. L. Ellis, devoted the facilities of their laboratory at Lynn, Mass., to research in this direction, and succeeded in making some good fused-quartz discs up to 12 inches in diameter and larger. But the cost was very great; equipment required to make one 200 inches in diameter by the method devised by Dr. Thomson would be prohibitively expensive. Quartz may be the perfect mirror material of the future, when means have been found to make large pieces of it inexpensively and with a minimum of uncertainty, but long years of development work have yet to be done, and the Observatory Council decided not to wait.

All candidates but borosilicate glass having been eliminated, intensive research was commenced to improve its characteristics for large discs, and work out ways and means of making the casting.

Fortunately, a body of experience in making large discs had been growing in this country for several years. Before 1917 most glass of this sort had been manufactured abroad. Indeed, there were some scientists who held that America had neither the materials nor the skill to produce it. When the foreign supplies were cut off, one of the first acts of the United States Government was to stimulate research in the manufacture of optical glass. Experts were sent promptly into the country's glass factories, to hasten production of the material so sorely needed for wartime instruments.

One of these experts was Dr. George W. Morey, of the Geophysical Laboratory of the Carnegie Institution of Washington. He was "loaned" to the Spencer Lens Company, of Buffalo, N. Y. Dr. Morey turned his attention not only to the manufacture of suitable lenses, but also to astronomical mirrors. His work, continued by Donald E. Sharp, glass technologist and later manager of the Spencer Lens Company's plant at

Hamburg, N. Y., resulted between 1920 and 1922 in the production of several notable mirror discs, one of the best being a 40-inch now in service in the Steward Observatory's large reflector—the first all-American telescope, from glass to mounting, in the country.

The 40-inch was not only the first large disc successfully cast here following the war, but was the first to be annealed according to the precise Adams-Williamson formula developed at the Geophysical Laboratory. While previous discs had been made—a 60-inch was produced by the Standard Plate Glass Company of Butler, Pa., as early as 1895*—the work by Morey, Sharp, and Sharp's skilful associate, Walter H. Rising, may well be said to have started the modern telescope disc industry in this country.

The experience was further developed in 1928, when the U. S. Bureau of Standards undertook to make the 69-inch disc for Perkins Observatory. For this, a borosilicate glass was used, and under the direction of A. N. Finn, of the Bureau, satisfactory methods of pouring and annealing were worked out, resulting in an excellent casting.

But the real problem had yet to be solved: the production of glass sufficiently low in expansion to overcome the inherent difficulties of a disc 200 inches or more in diameter. Neither in the Bureau of Standards' disc nor in the discs made by the Spencer Lens Company had an expansion coefficient been obtained which would really be called "low." This achievement remained for the Corning Glass Company, of Corning, N. Y., where the low-expansion borosilicate glass widely known under the trade-name of Pyrex—and later a special glass for the 200-inch telescope—was developed.

What this glass means to telescope-makers can best be understood by comparing the Corning Glass Company's product with other types. If the figure 100 is taken to represent the expansion coefficient of ordinary crown and flint glass, the Spencer Lens Company's 40-inch disc would rate about 95; the Bureau of Standards' disc about 80; early Corning Glass Company

* See page 157 and following.

Pyrex discs, such as are used in the solar telescopes at Mt. Wilson Observatory, about 33, and finally, the 200-inch disc about 26. On the same scale, pure silica glass ("quartz glass") would rate about 5½, but it has not been made in sizes larger than about 30 inches.

IV

The first attempt to pour a disc for the 200-inch telescope commenced at Corning, N. Y., on the morning of March 25, 1934. To make sure of the method, several discs, including one 120 inches in diameter, to be used later in testing the figure of the 200-inch mirror, were poured, annealed and sent on to Pasadena.

An important part of the preparation for this huge task was the construction of the mold. Generally speaking, a glass disc for mirror purposes should have a thickness of about one-sixth its diameter. This is necessary to give rigidity, but it adds enormously to the weight. The 200-inch disc, had it been plane on both sides, would have been about thirty-four inches thick, weighing in the neighborhood of forty tons.

But the designers found another way to provide the needed rigidity. It was accomplished by covering the bottom of the mold with a cellular structure consisting of triangular and circular projections, forming a geometrical pattern. When the glass was poured, the molten material ran between these humps, molding a ribbed pattern into the back of the disc. The pattern was designed not only for rigidity but also to provide places for the fingers of the mounting to engage the glass.

The adoption of the patterned mold made it practicable to decrease the weight by nearly half. The disc as finally cast weighed twenty tons. The molten glass was conveyed to the mold in cauldron-like dippers on trolleys, controlled with 20-foot handles. It required more than a hundred ladles of glass to fill the mold. Pouring began about 9 o'clock in the morning and continued all day, while blasting jets of incandescent gas kept both the melting furnace and the mold—which had been

domed over with firebrick to conserve heat—at a temperature of about 2000 degrees Fahrenheit.

To allow for grinding down possible rough edges, the disc as poured was 201 inches in diameter.

A slight accident marred the pouring of the first disc: two or three of the projections in the bottom of the mold broke loose and floated to the top, where they were fished out. Unable immediately to gauge the extent of the damage, the authorities at Pasadena decided to pour another as soon as possible. The mold was re-designed to prevent recurrence of the trouble. The second disc was poured without mishap, and ten hours after the pouring began it was safe in its annealing oven, to lie there for eleven months, cooling so gradually that all internal stresses had ample time to adjust themselves.

The second disc was selected to become the mirror for the California Institute of Technology's telescope. But the first, upon examination, was also found to be in good shape, and by drilling holes where the cores had floated out during the casting could have been made into a perfectly satisfactory mirror. By this accident, therefore, two 200-inch discs of low-expansion glass are now in the world. It is conceivable that money will be found some day for the construction of a second 200-inch telescope—perhaps for the southern hemisphere.

V

The second great problem of the 200-inch telescope was this: how should the monster be mounted to obtain the widest possible sweep of the heavens, with least friction, at least cost, and with the watch-like precision of movement necessary for photographing the stars?

It is possible, when the various items are totted up and compared, that the making of the mounting for the 200-inch telescope will rank as one of the greatest engineering feats of our age; comparable in difficulty with such projects as Boulder Dam, Grand Coulee, Mississippi flood control or the Los Angeles water system. For the mounting as completed is as tall as an eight-story building and weighs in the neighborhood of 1,000,000 pounds; is so huge that there is an astronomical laboratory within the moving parts of it—yet it is so delicately poised on almost frictionless bearings that the touch of a hand will move it. A quarter-horsepower motor is sufficient to drive it across the sky in its nightly vigil with the galaxies.

Not by a single step, nor from the brain of any one man did the design come into existence. The Observatory Council had certain requirements that must be met: the mounting must necessarily be of the equatorial type; it must provide for the use of several different optical systems; it should hold the optical parts rigidly and protect them from accidents and shock, as from earthquakes; it must be convenient to use, and come as near as possible to giving the mirror a full sweep of the heavens, from the Pole Star to the southern horizon.

Optical requirements also were fairly definite. The largest mirror in the world was to have a focal length most unusually short, in order to concentrate the light strongly into a small image and hence increase the power for photographic purposes. Whereas the 100-inch mirror has a focal length of 41 feet, or 5 times the diameter of the mirror, the 200-inch has a focal length of about 55 feet, or only 3.3 times its diameter.

It was the problem of the designers of the mounting to consider all of these requirements. They had, in addition, to decide among all the possible standard types of equatorial mountings, and a bewildering variety of experimental ones, some of which offered solutions afforded by none of the conventional designs. A sturdy "split-ring" type of equatorial mounting devised by the artist and telescope-maker Russell W. Porter engaged the attention of the committee for some time. A special virtue of the design is the wide and unobstructed view of the heavens it affords. The committee at length decided against it, principally because of the difficulty of removing the mirror.

A second type carefully studied was a modification of the fork-type mounting such as used successfully on the 60-inch at Mt. Wilson and a score or more of other large telescopes. A design suitable for the 200-inch was planned in detail by Dr.

Pease, of Mt. Wilson, and was subjected to careful study and computations by Professors Epstein and Martel of the California Institute of Technology, and Messrs. Gano Dunn and Samuel R. Jones of the J. G. White Engineering Corporation. In the process it developed weaknesses, and so it, too, was rejected.

The committee ended, in fact, by producing an entirely new design; one which perhaps should be called the "Palomar mounting." In some respects it resembles the rectangular polar mount of the 100-inch telescope; it bears also some family resemblance to the Porter equatorial, especially in its horseshoe-shaped north bearing. But beyond these hints of its ancestry it is distinctly a new type; sturdy, blunt-nosed, suggestive of power and purpose—more nearly resembling some futuristic gun than a telescope; and possessing a remarkable, impelling sort of beauty.

Most of the design came from engineers and astronomers connected with the Observatory Council; some points were provided by the intensely practical Captain C. S. McDowell, of the United States Navy, authority on naval engineering and research problems, who was "borrowed" by the California Institute of Technology to see to the construction. At least two important items, the oil-pressure bearings and the declination axis trunnions, came from the engineers of the Westinghouse Electric & Manufacturing Company, which was selected to fabricate the mounting at the huge Westinghouse turbine plant in South Philadelphia.

The Polar Axis (see Plate 30) consists principally of two parallel braced tubular members, yoked at the south end to a ball-and-socket bearing, meeting at the north end in a horseshoe-shaped member which serves as the north bearing. Between the tubular members of the polar axis swings the telescope tube, supported by trunnions which, though rigid in every other direction, have a small degree of flexibility laterally. This is made possible by an interesting "double-bicycle-wheel" construction, the five-eighths inch steel spokes of which are each under 3,000 pounds tension. This construction, aided by other devices, protects the optical parts from strain in the various

positions of the instrument, and is counted upon to take up a portion of the shock in case of earthquake.

Observers ride the instrument across the skies. At the prime focus there is provided a small capsule-shaped car, reached by a catwalk (see Plate 31), and suspended on knife-edges of steel. This little car contains photographic equipment, auxiliary mirrors for changing the focus, and the Ross lenses for correcting the image.

The Cassegrain focus is reached by elevator from the observatory floor. The observers ride a platform swung from the blunt rear end of the tube, beneath the cellular structure supporting the mirror. For the two modified Cassegrain foci, an air-conditioned, temperature-regulated laboratory is provided beneath the floor at the south end.

The most unusual observing-place of all is tucked into the eastern parallel member of the polar axis. These members are tubular, ten and a half feet in diameter, and the interior easily reached through doors in the saddle-shaped south yoke. Because the observers in the parallel member would otherwise be continually thrown off balance by the motion of the telescope, the tubular spectrographic laboratory is provided with a roller-bearing floor which automatically levels itself, and with a self-leveling table for the spectrograph. It can be entered comfortably, no matter what the angle of the telescope, by means of a stairway made of conical steps.

The material of the mounting is ordinary carbon steel, which was found to be most suitable. The lightness and sturdiness of the design was made possible by electric welding, which permitted thousands of pounds to be stripped off, and millions of rivets and bolts to be omitted. The first step in manufacture was the construction of a scale model in celluloid, one-thirty-second actual size. This was tested for deflections as a final study of the design before actual construction commenced, in 1936.

Even the enormous Westinghouse turbine works at South Philadelphia was too small to permit the complete assembly of the mounting before its final erection in California. During

construction, pieces that required precise fitting were put together, then taken down again for shipment. In this manner the entire mounting was assembled serially, the parts checked up, and the accuracy of fit determined. The most intricate jobs proved to be construction of the flexible trunnions of the declination axis (which required the utmost precision) and the machining of the south and north bearings. It proved necessary in fact to ship the horseshoe-shaped north bearing to the Westinghouse plant at East Pittsburgh for its final machining. This member alone weighs 317,000 pounds; its outside diameter is 46 feet. The bearing surface was machined as smooth as glass on the giant floor mill at East Pittsburgh, one of the largest in the world. To carry out this operation within the tolerances allowed, a special "sunbonnet" was placed over the giant disc of metal to protect it from the midday sun which, streaming through the glass of the factory roof, produced enough expansion and variation to throw the calculations out.

On the glass-smooth surface of the north and south bearings the telescope moves from east to west following the stars. The great weight is supported upon metal pads beneath the bearings, but there is no contact of metal on metal. By means of an ingenious system originally developed by Westinghouse engineers for the bearings of large balancing machines, the huge telescope is actually floated on oil, at 250 pounds pressure. The bearings slide over their supports like a wet beer mug on a slippery table. The energy needed to move the instrument across the skies is calculated at only 1/165,000th horsepower—about one flea-power. For practical reasons, of course, a somewhat larger motor is supplied.

VI

Ordinary description is powerless to convey a proper sense of the magnificent proportions of this telescope. Photographs fail to reveal the true size of it.

The tube itself, square in cross-section, is 22 feet one inch in diameter and approximately 60 feet long. The prime focal point at the top is exactly 666 inches from the surface of the mirror. The tube is a welded structure consisting of two main rings held together by struts. At its middle a square steel box-like construction gives place for the trunnions to connect it to the yoke.

At its lower end the tube is gripped by the mirror cell. At its upper end the prime focus cage, a little over 22 feet in diameter and 10 feet high, holds the observer's post, which is six feet in diameter, split horizontally into two compartments, and hung on thin strips of steel set edgewise to the incoming beam of light.

The entire weight of tube, mirror, mirror cell, prime focus cage and observer's post—the whole portion of the mounting pivoted on the declination axis—is 240,000 pounds.

More massive still is the polar axis. The yoke girders of the axis are made of hollow steel tubes, each 60 feet long and ten and a half feet in diameter, constructed of one-inch steel, rolled and welded with one seam. The horseshoe-shaped north bearing is 46 feet in diameter. It is made of steel three and one-half inches thick; the construction being that of a hollow, welded box, with stiffening members welded inside. Space for counterbalances of concrete and cast iron is provided in the tips of the horseshoe.

The slotted construction of the north bearing permits the tube to swing northward to the circumpolar region. This slot is 22 feet six inches wide. When the telescope is pointed north, there is a two and one-half inch clearance between the tube and the sides of the horseshoe.

The other end of the polar axis is a yoke tying the parallel tubular members to the ball-and-socket south bearing. The yoke is 46 feet long, 10 feet six inches deep and five feet wide. The ball-shaped thrust bearing, seven feet in diameter, is carried on three huge babbitt-surface palms inside its socket. These do not touch the metal, but support the oil under pressure which actually carries the load.

The thrust bearing is hollow. Through its center comes the shaft which drives the polar axis east or west.

The total weight of the polar axis alone, without the tube and other members that move on the declination axis, is 830,000 pounds.

The height of the telescope complete, with the tube pointing straight up, is 75 feet. Its total weight is more than 500 tons.

VII

In 1903 Mt. Wilson was selected as the site for a new observatory by Dr. Hale himself, after preliminary inquiries by Professor Hussey and a few months of testing.

The site for the new observatory of the California Institute of Technology was chosen by much more elaborate methods; its approval followed a nation-wide search for the right location, pursued by every means known to astronomical science.

Certain natural limitations both as to latitude and altitude must be observed in selecting sites for large telescopes. If the observatory is located too far north, the bulk of the earth will cut off important areas across the celestial equator which can be observed from stations near the middle of the temperate zone. On the other hand, if it is too far south, the circumpolar stars will not rise far enough above the horizon.

Between the latitudes of 30 and 35 degrees north, approximately three-quarters of the entire celestial sphere can be observed. Mt. Wilson is in this region, which in California takes in a strip of the coast reaching from Fresno to well out in the Gulf of California. Most of Texas, New Mexico and Arizona lie within it, as well as the Southern States in the belt lying between Tennessee's northern boundary and Georgia's southern line.

To obtain the fullest view of the sky the observatory necessarily must be located somewhere in this zone. The problem was to discover within it a suitable mountain peak, high plateau or other vantage-point upon which to build the structure.

Many secondary problems and some major ones enter in. If the site is too high, for example, the weather will be cold most of the year, and the work of the observatory will be diminished

both in volume and accuracy. The dome of an observatory obviously cannot be heated. The scientists necessarily have to work under the same conditions of temperature as those to which their instruments are exposed, and no man can hold a photographic negative upon the exact centers of shivering star images while his hands are numbed with cold or made awkward by gloves.

Experience has shown that the practical altitude of a suitable mountain or plateau site lies below 6,000 or at most 8,000 feet. The problem that remains is to select from among a number of such places, otherwise suitable, the one where the best seeing is to be found for the greatest number of days and nights in the year.

Many sites near enough to cities to be convenient, surrounded by country permitting of easy access, and possessing other qualifications, were carefully tested with refracting and reflecting telescopes for the quality of the seeing and the number of nights in an average year when telescopes would be useful there. A new method of testing for good seeing was used in this work. Instead of grading sites by the customary plan of estimating the quality of the star image, according to a scale in which 0 is very bad, 1 bad, 2 not so bad, 3 fair, 4 better and 5 good, with 10 for practically unattainable perfection, a more scientific and accurate method was adopted of measuring the size of the disc which a star makes on the photographic negative.

This circular area does not represent the actual disc of the star, but is produced by the wandering image on the plate, caused by atmospheric disturbance, slight vibrations that affect the instrument, and other factors. The movement of the image is at random, and in time it moves in all directions. The result is finally a circular white spot, considerably larger than the actual point of light cast by the star at any instant of time, and aptly called a "tremor disc."

The magnitude of the tremor disc is caused by several factors, of which the mechanical ones are vibrations in the telescope and the length of exposure. But all other things being equal, a chief cause is the aberration produced by the turbu-

lence of the air. If the same instrument is used at various sites, with identical exposure times, the diameters of the tremor discs made by certain reference stars give an accurate index of the quality of the seeing.

A quick way of measuring the diameter of the tremor disc was devised by Dr. Anderson, and given a thorough test at Mt. Wilson with small telescopes, checked up by the 100-inch and 60-inch telescopes. It was found to be both accurate and convenient. Testing of sites was then commenced with ten portable refracting telescopes especially fitted up for such use. Two 12-inch Cassegrains, designed by Russell W. Porter and provided with rugged duraluminum mountings capable of withstanding mountain transportation by mule-back or man-back, were used in the final check-up.

With this paraphernalia, a prodigious amount of data was obtained on mountain sites, on plateaus, hills, flats and ridges. Crews of computers tabulated the results, compared them, and checked them up against the experiences of the investigators. The choice began to narrow to mountains in the West.

The final selection, as everybody knows, fell upon Mt. Palomar, a location of most unusual beauty, readily accessible; shaped up as if by some providential hand for use as an observatory. Its altitude is 6,126 feet. The seeing is expected to prove as good as that at Mt. Wilson if not better. It is eighty miles, north and east, of San Diego, Calif., to which it has now been connected by highway. A large tract has been obtained by the California Institute of Technology to protect it against encroachments that might damage its astronomical usefulness. Magnificent observatory buildings have been constructed.

And there, late in 1938, began to arrive the parts of the great 200-inch telescope, just ten years after the first appeal for financial aid for this project appeared in the pages of an American magazine. There too began to focus the astronomical attention of the world. In anticipation of new discoveries to come, engineers and scientists were bending every effort to make ready for the great mirror slowly taking its final form in the optical shop in Pasadena.

A great deal of nonsense has been written about the possibilities of new discoveries with the 200-inch telescope. Some writers have estimated that it will bring the moon within an apparent distance of twenty-five miles of the earth; others that it may disclose inhabitants on Mars, or that it will enable astronomers to study the planetary systems (if there are any) of nearby stars. These speculations are based on the theoretical magnification of the telescope, but of course the practical magnification is limited to a fraction of this power by the inherent difficulty of seeing through air. Actually, the 200-inch will magnify no more than many a smaller telescope now in use.

Nevertheless, it may well be the greatest telescope venture of all time. For when the mirror is at last complete, this astronomical kodak—"the biggest miniature camera on earth"—will make possible a plunge into the abysses of space greater relatively than that taken by Herschel when, in the 1780's, he made his great reflecting telescopes and discovered the composition of the Milky Way, disclosed the gleaming "island universes," and plucked from its hiding the planet Uranus. The 200-inch will probably tell us little that is new about our nearest neighbors, but who can say what it will disclose in the farther view—over a billion light years into space? More spiral nebulae, perhaps; more portions of the universe continually flying from us; more worlds and galaxies in actual states of birth, growth, old age and final dismal extinction. It may be that we shall see matter being made from nothing; atoms transformed into energy, and energy back into matter. Or perceive the curvature of space, if curved indeed it is. Or it may be that celestial objects more fantastic than any yet imagined will come into view, so far away the very light disclosing them will have left before the beginning of this tiny earth.

In the year 1947, or thereabout, the great mirror will be completed, carried to its mountain, and adjusted in its steel cradle beneath a dome that now stands empty for it, staring blank and eyeless at the sky's slow nightly march. Until then, what the 200-inch telescope will actually reveal about the vasty universe must remain an unanswered question.

Chapter XVIII

TELESCOPES OF THE FUTURE—HAS THE ULTIMATE BEEN REACHED?

I

AT least three, and perhaps four or more times in the course of astronomy, men have considered that at last the ultimate in discovery through larger or better instruments had been reached. Surely Tycho Brahe and his contemporaries reasoned that larger, finer instruments would never be made than those of Uraniborg; hence with Tycho astronomy must reach its ultimate development, with only minor discoveries and small rewards for those to follow.

Again, it is conceivable that old Hevelius and Christiaan Huygens, when they finished their unwieldy, long telescopes, thought that no instruments would ever be made finer, or better, or more powerful. Yet they were mistaken. We may assume that the Dollonds, with their achromatic telescopes of small aperture, thought nothing appreciably larger would ever be built because of the lack of suitable glass, yet Guinand the glass-maker and Fraunhofer and Clark the telescope-makers speedily proved them wrong, and today there are 26-inch—36-inch—40-inch refractors.

And how about the great mirrors of Sir William Herschel and Lord Rosse? Were they not the ultimate in figure and magnitude? Surely Lord Rosse, when he toiled to construct his 6-foot speculum-metal mirror, thought no telescope would ever exceed it in size. The extreme difficulty of casting the metal and giving the mirror its final polish and figure would preclude it. But this, too, was wrong. The Hooker telescope at Mt. Wilson is approximately three feet greater in diameter than his, and we

shall have at Mt. Palomar an aluminum-on-glass reflector of 17-foot aperture.

How, then, shall we answer those who say that the coming 200-inch telescope will be the last and greatest of the huge reflectors? Against their doubts can be set the faith of the man who made the 60-inch and 100-inch reflectors possible, and who was the moving spirit of the enterprise which will bring us the 200-inch. Dr. Hale believed that there would be a gain in the 200-inch telescope fully commensurate with its larger diameter, and that telescopes of even greater aperture—possibly up to 300 inches, would give proportionate gains. Moreover, designs for the mounting of such a 300-inch telescope have already been drawn up at Mt. Wilson Observatory; they are certain there that no insurmountable problems are involved, so far as the mechanical and optical work is concerned.

With this expert opinion the testimony of the interferometer in the hands of Dr. Pease concurred. A 300-inch telescope at Mt. Wilson or some other spot of equally calm air would be able to bring in the universe almost as readily, and on nearly as many nights of the year, as the 60-inch and 100-inch telescopes.

And what would such a 300-inch telescope be able to accomplish, assuming the same focal ratio as that of the 200-inch, and assuming that the seeing would be equally good?

It would be able to reach out photographically nearly 2,700,000,000 light years into space. The diameter of the whole universe, according to calculations of Dr. Edwin P. Hubble, cannot exceed 6,000,000,000 light years. Therefore the giant telescope we contemplate could very nearly see through a complete radius of the universe, and disclose to us what, if anything, composes its outer shell.

It would make possible a study of the major portion of the 500,000,000,000,000 island universes which Dr. Hubble estimates are contained in the universe he has calculated. It would resolve the separate stars of some of the nearer ones, so that the state of matter in galaxies other than our own could be investigated by individual stars instead of in the mass.

It would, just possibly, solve the major problem toward which

all astronomical research is groping: What is the universe, and has it beginning or end—or purpose—so far as man can learn? With a greater eye, of penetration approximately equal to the radius of the universe, there would perhaps become apparent the true form of the nebulæ-filled cloud in which we now seem to be enclosed. And with its appearance might come enlightenment.

II

The interferometer and the designer's pencil say that the 300-inch telescope would be possible and useful. But there is another matter to be considered.

In his booklet describing the new McDonald Observatory, Dr. Otto Struve, director of Yerkes Observatory, points out that in 1824 the most powerful telescope in the world, the ten-inch refractor made by Fraunhofer for the University of Dorpat, cost 10,600 guldens, or about $3,100.

The total cost of the Yerkes 40-inch refractor, installed in 1895, including optical parts, mounting and dome, was $166,000.

The 100-inch Hooker reflector, completed in 1919, cost approximately $650,000.

And the total outlay for the 200-inch telescope came very near to $6,000,000, including the mounting, dome, optical parts and auxiliary equipment.

Thus the cost of telescopes has not only increased with time, due to higher wages and higher costs generally in our day, but the expense goes up much faster than the size, the price skyrocketing ahead of each increase in aperture.

What would be the outlay for a 300-inch telescope? No one can say; yet it would surely exceed that of the 200-inch by two or three times, at the very least. Is there any capitalist today, any foundation or scientific group—even any nation—willing or able to give $15,000,000 or more for the construction of a 300-inch telescope? These are times when armies, battleships, and the materials of war call forth seemingly inexhaustible rivers of money, but the needs of astronomy may fare less well.

Lacking a Mæcenas, therefore, we shall have to be content for the time being with the ordinary 100-inch and 200-inch telescopes, or look about for a substitute for telescopes—a new invention, if you please, that can replace the mirror with equal resolving power at less cost.

The question is, can there be such an invention?

III

In 1933, Dr. Vladimir K. Zworykin, engineer of the RCA Victor Company, of Camden, New Jersey, proposed before a gathering of radio engineers that the problem of television could be solved with an instrument he called an "iconoscope."

The principle of this ingenious contrivance is identical with that of the photoelectric cell, except that instead of a single sensitive element the iconoscope provides a small mica disc studded thickly with tiny cells consisting of microscopic dots of silver, evenly laid over the mica but not touching each other.

If a beam of light falls upon such a "photoelectric mosaic," a small electrical charge will be built up on each of the silver beads, due to the photoelectric action of light. The magnitude of the charge on each silver bead will be proportional to the intensity of the light received by it, and tho in any case the charge will be minute, a suitable condenser, which may be merely a solid metal disc affixed to the back of the mosaic and insulated from it by the mica, will store up the charge until it becomes great enough to be detected with suitable apparatus.

If the beam of light passes through a lens, and an image is thus thrown upon the mosaic, the magnitude of the charges on the silver-dot pattern will reflect faithfully the various intensities of light on the different parts of the image. There will thus be formed a kind of invisible "electrical image" in the mosaic.

But how can the magnitudes of all these tiny charges be determined? After ten years of experiment Dr. Zworykin has devised a most ingenious method of accomplishing this seemingly impossible task. A small "scanning beam"—a ray of electrons—sweeps rapidly over the mosaic, discharging the tiny silver photocells one by one. As this is done, the negative

charge on the condenser at the back of the disc is released by just so much as there was positive charge on the silver dot at that moment being scanned by the electron beam. A pulsating current passes from the condenser over a wire and through an amplifier, which increases it in the same manner as the feeble current generated in a radio is stepped up by its amplifying tubes until strong enough to operate a loudspeaker.

Herein lie the marvelous possibilities of this new instrument, for if the resolving power is sufficient, the electrical counterpart of the image can be magnified a thousandfold or more, and when it is again reproduced as light—with the aid, say, of a second electron beam and a fluorescent screen—the original image can be made both larger and brighter. Magnification indeed, done electrically!

Of course, there are obstacles, and serious ones. The resolving power of such a device will depend upon the number and smallness of the sensitive silver dots that can be made into a suitable mosaic, and upon the narrowness of the electron-beam pencil that scans the mosaic to release the charges. To obtain the sharpest possible resolution, the silver dots will have to be no bigger than a single wave-length of light, and the electron beam so narrow that it can discharge only one of these ultramicroscopic globules at a time.

Whether such perfection can even be approached remains to be seen, but considering the ingenuity of engineers in the past in overcoming difficulties that seemed even more formidable, there is no need to despair at this stage of the invention's development.

By evaporating a thin film of silver, causing it to break up into tiny beads, several millions of separate photo-elements can be readily produced per square inch of the area of the mosaic, Dr. Zworykin reports. Now the wave-length of red light is somewhat less than one thirty-thousandth of an inch, and that of the short waves at the other end of the spectrum not quite half so much. Therefore, if the fine pattern of silver dots can really be made as minute as Dr. Zworykin says, we shall still be a long way from attaining the necessary fineness for optical purposes.

For complete resolution in red light no fewer than the square of 30,000 dots, or 900,000,000, will be needed in each square inch. For blue and violet light the mosaic will require between three and four billion dots per square inch throughout its surface.

A suggestion that this and other obstacles may nevertheless be overcome, and a telescope built which for all practical purposes will be more powerful and more useful than a 200- or 300-inch instrument at a fraction of the weight and expense, was made before the American Association for the Advancement of Science at Boston in December, 1933. This prediction was by Dr. François Henroteau, of the Dominion Observatory, Ottawa, who reported that he himself was carrying on experiments toward this end. Others undoubtedly are giving it study also.

In the meantime astronomers will watch with greatest interest the progress of the new science of television. The great advances in this branch of electronics during World War II are such that Dr. Zworykin's suggested "photoelectric telescope" may be closer than most of us realize.

What new wonders of space may appear as a result of this stimulating approach toward a new type of telescope must be left for the future to reveal. It is evident, however, that the principle of the photoelectric mosaic, or as some term it, the "artificial retina," has enormous possibilities. Here is a field in which some amateur astronomer or instrument-maker, versed in electronics and skilled in metallurgy, may make an invention of transcendent importance to science. For given great sensitiveness to light and sharp enough resolution to afford large amplification, a small mosaic of this kind could, indeed, be made to do the same work as a large telescope. Such a mosaic, placed, say at the focus of a 200-inch mirror, might well make bigger instruments superfluous.

IV

But the larger mirror and the artificial retina, however attractive, can never solve the major problem of outwitting the atmosphere. So long as astronomers are forced to look up

through 200 miles or so of air that swathes the earth like a shimmering blanket, the stars will continue to dance or blur; the telescope will be at the mercy of wind and rain and storm and atmospheric ripples; and only such light as can filter down to us through radiation-thirsty molecules may be used to record the marvels of the heavens on photographic plates, or yield the composition of stars and nebulæ to the analytical spectrograph.

Astronomers with an imaginative turn of mind have often gazed longingly at the rough and pitted surface of the moon. What a superb, what a magnificent location that for an observatory! The moon has no disturbing atmosphere; moreover, her gravitational attraction is so small as compared with that of the earth that instruments so large as to be totally useless on earth could be manipulated there with ease. But how shall we get to that fair vantage-point, so near as viewed, say, through the Yerkes 40-inch telescope, but so far away in actual miles? Here, too, we see a ray of hope in an invention which has long been talked about, the rocket. There is no theoretical reason why the rocket cannot take us to the moon, or to Mars or Venus, for that matter.

This dream, too, has been brought immeasurably closer by the developments of World War II. We may presently see rockets sent into the stratosphere, carrying meteorological instruments for systematic studies of the upper atmosphere and the development of controls.

The next step will be to send rockets out of the atmosphere —a distance of perhaps 200 or 300 miles—with automatically operated instruments for making astronomical observations and recording them during the precious moments between the end of the ascent and the beginning of the descent.

Then we may finally have rockets capable of leaving the earth altogether. An outward velocity of 6.664 miles a second, theoretically attainable with atomic power and even from certain chemical fuels, will provide sufficient momentum to send a rocket forever beyond the reach of the earth's gravitational hold.*

* For discussion of these possibilities, see the author's book *The Coming Age of Rocket Power* (New York, Harper & Brothers, 1945).

With such a rocket we might go to the moon and open an observatory there.

As an intermediate step, it has been suggested that a velocity of about five miles a second, much easier to attain than the theoretical speed of liberation, would transform a rocket into a permanent satellite of the earth, forever swinging around the globe like a lesser moon, safely clear of the atmosphere.

Such an observatory in space perhaps could be serviced like a lighthouse, by occasional rocket shots from earth with supplies and new photographic plates. It could be made quite comfortable and quite large, for the addition of weight, so long as all parts partook of the critical velocity, would make little or no difference.

Imagine these astronomers of the future, riding in peace and quiet in an enclosed observatory 1,000 miles or so above the surface of the earth, free to view the stars in any direction and at any time, utterly without the atmospheric troubles that beset observers on the earth!

V

But in our speculations we need not be content with this, for the moon still beckons as the ideal spot for an observatory. The moon is barren, airless; supplies would have to be brought at intervals, and the observatory would need to be an airtight, temperature-controlled place; perhaps a sort of giant thermos bottle.

It might be a relatively simple matter to roof over one of the smaller craters with a double thickness of glass, made on the spot by fusing sand with the aid of the solar heat. Under this vitreous roof would be built the city of the astronomers, with telescopes as large as they could wish, and perfect seeing unlimited the clock around.

It is true that their movements outside the air-conditioned crater would be somewhat hampered; nevertheless exploring parties could certainly get around with the aid of "space suits" supplied with air by suitable apparatus. A suit of this kind

already has been developed by a British inventor, and he hopes to use it in a stratosphere balloon ascension. Aluminum foil, the lightest and most efficient heat insulator known, protects the wearer from the cold of the stratosphere or space. Liquid air in a double-walled Dewar flask provides him with fresh air to breathe for several hours between refills, and a simple valve arrangement permits the expired air to escape. Even the difficulty of stiffness, due to the swelling out of the suit because of the air pressure within, has been overcome by this inventor, who employs special joints in the suit at shoulders, elbows, hands, thighs and knees.

On the moon the effect of gravity is only one-sixth that on earth. Hence, while a 200-inch mirror may weigh twenty tons here, it would weigh only a little more than three tons on the surface of our satellite. For the same quantity of metal in the mounting, then, a mirror six times as large could be operated on the moon. Moreover, because the effect of flexure in the glass would be less than on earth, a much thinner disc would do, making it feasible to put most of this enlargement into the diameter and not so much in increased thickness. We might, therefore, find mirrors of 100 feet or more convenient instruments on the moon, capable of collecting nearly 300,000,000 times as much light as the human eye, and of seeing into space nearly 150 times farther than the 100-inch telescope—possibly the stupendous distance of 45,000,000,000 light years. If, as Dr. Hubble estimates, the whole diameter of the universe is only 6,000,000,000 light years, this would be seeing beyond it indeed!

Should this still prove insufficient to solve the problems of astronomy, we might in fancy venture further. The moon's low gravitational field makes it an attractive place from which to take off for a journey to another planet—say to Mars. There we shall find the seeing not quite as good as on the moon, but immeasurably better than on earth. Mars has a thin atmosphere, in which clouds occasionally are observed to float, but for the most part this planet is dry and the air clear.

The advantage of an observatory on Mars over one on the moon or earth lies in the fact that the red planet has a larger

orbit than the earth; hence provides a greater baseline for the measurement of parallaxes and the like. The Martian parallax of a star would be the angle subtended at the star by a baseline nearly 150,000,000 miles in length, half again as long as that afforded by the radius of the earth's orbit, providing an angle half again as large. From Mars the parallaxes of thousands of stars could be measured which are too far away to yield a parallax by any direct means on earth.

Pushing even further afield we might, if large and powerful rockets were to be developed, move outward from the sun even to one of the attractive satellites of Jupiter. Such a site would give us advantages similar to those provided by the moon, and in addition, an orbit (shared with Jupiter) more than five times as large as that of the earth. From Ganymede, let us say, it might be possible to measure by direct methods the distances of a good portion of the stars of our galaxy, certainly an appreciably larger part of them than can be obtained either from the earth, moon or Mars.

As for Jupiter itself—we should probably not care to land there, for the attraction of gravity at the surface would be nearly three times that of the earth. A 150-pound man would weigh a quarter of a ton on Jupiter, and would experience the greatest difficulty in moving from one place to another. But on Ganymede gravity would be about the same as on the moon. This satellite would probably also be airless and resemble the moon in other ways, except that the light of the sun would be much less intense. Our hypothetical astronomers would have to get used to protecting themselves from a temperature little above absolute zero, but they would not, as on the moon, find it necessary to provide shields against the boiling heat of the moon's two-weeks-long day.

VI

Are we limited to the solar system? Very likely, if man-made vehicles are used to carry us about. The rocket, which may some day provide a means of traveling about at speeds up

to ten miles a second, could not take us to the nearest star even in a lifetime of travel.

But one other possibility should be considered before we leave off fantasy. That is the chance—however rare it may be—that other stars have planetary systems, that some of those planets are inhabited by intelligent beings, and that we shall sometime, somehow, find a means of communicating with them.

Should such a marvelous community of minds occur across the gulfs of space, a sort of league might be organized to tackle the problems of astronomy. The people of Vega's planets, let us say, could see much that we cannot, or see it from a different point of view. From the planets of the dim stars at the outer edges of the Milky Way might come knowledge obtainable in no other way. Finally—why not?—we could explore space through eyes of peoples inhabiting the planets that swing around stars of the Great Nebula in Andromeda, or of the as yet unresolved stars of nebulæ so far from earth that our finest telescopes can see them only as indistinct blurs.

But of course there is the question of how such communication might be established, forgetting for a moment all the other ifs that crowd about, clamoring for attention. It is unlikely that we shall find any way to communicate which will carry a message faster than light. Therefore, a two-way telephone conversation with the people of the hypothetical planets of *Alpha Centauri*, the nearest of them, would require at least nine years to complete. If we sought to converse with peoples on the outer rim of the Milky Way we should have to be prepared to wait 100,000 years or more for our answer. And it would be a cosmic question indeed that should be put to the peoples of the Andromeda Nebula. More than a million and three-quarters years would of necessity elapse from the time of asking the question to receiving the reply!

VII

The case for observing from the earth may not be as bad as it has been painted. It is true that until we have the observatory in space or on the moon we shall not overcome bad seeing and atmospheric aberration. But there are some nights of the year, at almost any suitable site, when the atmosphere seems almost not to exist, and the light of the stars comes through clearly and steadily. Such of it as is absorbed by the air will always be lost, but this loss can be made up for, to some extent, by enlarging the aperture of our telescopes.

What is required is a substitute for the heavy glass mirrors of the present: either the electronic telescope or light-weight mirrors made of some sort of plastic, or of glass in new ways, perhaps in the cellular fashion, as suggested by Professor Ritchey.

Back about 1935 Ritchey made some plans for a "super-telescope" 315 inches in diameter, using the cellular mirror arranged in the Ritchey-Chrétien style. Such a telescope would have a theoretical magnifying power of 22,500 diameters on objects such as the moon, planets and nebulae, and 37,000 diameters when used to photograph star fields. Assuming it could be built, it would permit the photography of stars 100 times more distant, and only one ten-thousandth as bright, as any within reach of existing telescopes. It would permit photographing details on the moon seventy feet in diameter, details on Mars less than two miles across, the possible detection of planets around some of the nearest stars, and the photography of all classes of celestial objects so sharply as to increase the accuracy of measurements sixty-fold.

The super-telescope of the future as imagined by Professor Ritchey would be provided with a "fixed universal" mounting —the great mirror permanently fixed in place to avoid flexure of the mirror and the inefficiency of large telescopes when tilted. He would so figure the mirror of the super-telescope as to give it command of a circular field of the sky equal to a meridian angle of about fifteen degrees.*

In order to cover the whole field of the heavens Professor Ritchey proposed the construction of five or more such instruments, on sites separated by about twenty degrees of latitude.

* If built as a Schmidt camera it might cover an even wider field.

One would be located on the equator, two or more in the southern hemisphere and two or more in the north.

"A series of five super-telescopes in successive latitudes as outlined may well become a cooperative work of nations," wrote Professor Ritchey. "These telescopes may well become the mighty guns of peace. Nations will soon decide, and gladly, that all such efforts for human betterment, for science and education, are infinitely more interesting and more profitable than the wholesale mutilation and murder of our fellow men called war.

"The natural sciences are so closely interrelated that when a great advance is made in one all simultaneously move forward with it. The fixed universal telescope makes possible the use of accessory instruments for analyzing the radiation of stars and nebulæ. These instruments will be incomparably more powerful and refined than any which can be attached to the greatest movable equatorial telescopes, as at present. We shall thus learn of conditions of matter in the infinite laboratory of the universe, conditions which could never be imagined from our meager experience in terrestrial laboratories.

"This is the great adventure. These telescopes will reveal such mysteries and such riches of the universe as it has not entered the mind of man to conceive."

With such a picture it is well to close this book. Men and their mirrors have already discovered miraculous things in the space that encompasses us. What will the mightier mirrors of the future imprint upon the all-seeing photographic plate?

APPENDICES

Appendix I

THE WORLD'S LARGEST TELESCOPES AND WHERE THEY ARE LOCATED

Reflectors

200-inch: (to be finished about 1947); Astrophysical Observatory California Institute of Technology, Mt. Palomar, Calif.

100-inch: (known as the Hooker telescope); Mt. Wilson Observatory of the Carnegie Institution, near Pasadena, Calif.

96-inch: (not yet completed); to be located at the University of Michigan Observatory, Ann Arbor, Mich.

82-inch: McDonald Observatory of the University of Texas, Mt. Locke, Texas.

74-inch: David Dunlap Observatory, University of Toronto, Toronto, Canada.

72-inch: Dominion Astrophysical Observatory, Victoria, B. C.

69-inch: Perkins Observatory of the Ohio Wesleyan University, Delaware, Ohio.

61-inch: Harvard Observatory, Oak Ridge, Cambridge, Mass.

60-inch: Mt. Wilson Observatory, Pasadena, Calif.

60-inch: Harvard Observatory, southern station (Harvard Kopje), near Bloemfontein, South Africa.

60-inch: National Observatory of the Argentine Republic, Córdoba, Argentina.

48½-inch: Berlin-Babelsburg Observatory, Berlin, Germany.

48-inch: Melbourne Observatory, Melbourne, Australia.

47-inch: St. Michel, Haute-Province, France.

42-inch: Lowell Observatory, Flagstaff, Ariz.

40-inch: (Ritchey-Chrétien) U. S. Naval Observatory, Washington, D. C.

40-inch: Merate, Italy.

40-inch: Stockholm Observatory, Stockholm, Sweden.

40-inch: Simeis Observatory (a branch of Pulkowo Observatory), Crimea, U. S. S. R.

39½-inch: Hamburg University Observatory, Bergedorf, Germany.
39½-inch: Geneva Observatory, Geneva, Switzerland.
39½-inch: Meudon Observatory (a branch of the Paris Observatory), Meudon, France.
39-inch: Royal Observatory, Uccle, Belgium.
37½-inch: University of Michigan, Ann Arbor, Mich.
36-inch: (known as Crossley Reflector) Lick Observatory, Mt. Hamilton, Calif.
36-inch: Steward Observatory of the University of Arizona, Tucson, Ariz.
36-inch: Observatory of the Catholic University of Chile, Santiago, Chile (formerly the Chile Station of Lick Observatory).
36-inch: Royal Observatory, Edinburgh, Scotland.
36-inch: Royal Observatory, Greenwich, England.
36-inch: Goethe Link, Indiana.

Refractors

40-inch: Yerkes Observatory of the University of Chicago, Williams Bay, Wis.
36-inch: Lick Observatory of the University of California, Mt. Hamilton, Calif.
32½-inch: Meudon Observatory (a branch of the Paris Observatory), Meudon, France.
31½-inch: Astrophysical Observatory, Potsdam, Germany.
30-inch: Pulkowo Observatory, near Leningrad, U. S. S. R.
30-inch: Allegheny Observatory of the University of Pittsburgh, Pittsburgh, Pa.
30-inch: University of Paris Observatory, Nice, France.
28-inch: Royal Observatory, Greenwich, England.
27-inch: University of Michigan, Southern station at Bloemfontein, South Africa.
27-inch: University Observatory, Vienna, Austria.
26½-inch: Union Observatory, Johannesburg, South Africa.
26-inch: U. S. Naval Observatory, Washington, D. C.
26-inch: Leander McCormick Observatory of the University of Virginia, Charlottesville, Va.
26-inch: Yale University Observatory, Southern station at Johannesburg, South Africa.
26-inch: Royal Observatory, Greenwich, England.

Appendix II

SOME MODERN OBSERVATORIES IN NORTH AMERICA AND THE SOUTHERN HEMISPHERE, AND THEIR INSTRUMENTAL EQUIPMENT

There are more than 300 observatories in the world, of which about eighty are in the United States and Canada. Obviously this list makes no attempt to be exhaustive, but includes some of the more interesting and most-often-mentioned observatories.

North American Observatories

ALLEGHENY OBSERVATORY OF THE UNIVERSITY OF PITTSBURGH (Pittsburgh, Pa.)

Founded: 1860 by the Allegheny Telescope Association.
First Director: Philotus Dean.
Present Director: N. E. Wagman (acting).
Major Telescopic Equipment:
30-inch photographic refractor (Brashear).
30-inch Cassegrain reflector (Brashear).
13-inch visual refractor.
Principal Work: Stellar parallax and other photographic astronomy of position; precise laboratory and solar wave-lengths; photographic photometry.
Financed by: University of Pittsburgh and endowment.
Staff: Five members, including Keivin Burns, spectroscopy-parallax, double stars; N. E. Wagman, parallax; and Z. Daniel, parallax.

DAVID DUNLAP OBSERVATORY OF THE UNIVERSITY OF TORONTO (Toronto, Ontario)

Founded: 1935 by the widow and son of the late David A. Dunlap, of Toronto.
First Director: C. A. Chant.

Present Director: R. K. Young.

Major Telescopic Equipment:

74-inch reflecting telescope now under construction.
19-inch reflector.
Telescopic cameras.

Principal Work: Investigations of the motions and distributions of stars.

Financed by: University of Toronto.

Staff: Eight members, including:

C. A. Chant, professor emeritus of astrophysics and director emeritus of the observatory.
R. K. Young, professor and director of the observatory.
F. S. Hogg, associate professor.
J. F. Heard, assistant professor.
Mrs. H. S. Hogg, lecturer.
Miss R. J. Northcott, lecturer.
G. F. Longworth, observer.

DOMINION ASTROPHYSICAL OBSERVATORY (Victoria, B. C.)

Founded: 1916

First Director: Dr. John S. Plaskett

Present Director: Dr. Joseph A. Pearce

Major Telescopic Equipment:

73-inch reflecting telescope; 3-Prism Littrow Spectrograph; Stellar photometer and registering microphotometer.

Principal Work: Investigations of stellar motions. Spectrophotometric studies of the physical constitutions of the stars, nebulæ and comets. Determination of the masses and dimensions of eclipsing variables and binary systems.

Financed by: Dominion of Canada.

Staff: Director—J. A. Pearce, Ph. D., F. R. S. C.

Assistant Director: C. S. Beals, Ph. D., F. R. S. C.
Astronomers—R. M. Petrie, Ph. D., F. R. S. C.
A. McKellar, Ph. D., F. R. S. C.
K. O. Wright, Ph. D.
Assistants—Miss Jean K. McDonald, B. Sc.
Miss Joan Jackman
H. W. Dukeman
S. S. Girling, instrument maker

FLOWER OBSERVATORY OF THE UNIVERSITY OF PENNSYLVANIA (Upper Darby, Pa.)

Founded: 1896, by Reese Wall Flower.

First Director: C. L. Doolittle.

Present Director: Charles P. Olivier.

Major Telescopic Equipment:

18-inch refractor (Brashear).
4-inch zenith telescope.
4½-inch meridian circle.
4½-inch equatorial.
4-inch portable equatorial.
4-inch Ross-Fecker photographic telescope.

Principal Work: Double stars; photometry of variable stars; headquarters of American Meteor Society, hence reduction and publication of observations reported by members (about 60,000 yearly).

Financed by: Endowment.

Staff: Four persons, including:

Charles P. Olivier, visual double stars, variable stars and meteors.
S. G. Barton, search of astrographic catalog for doubles; visual double star work.

The University of Pennsylvania also operates the Cook Observatory at Wynnewood, Pa., founded by Gustavus Wynne Cook, and left by him to the university in 1940. Dr. Olivier is the present director, and the principal work is a Milky Way Atlas, on 30 x 24-inch plates.

GOODSELL OBSERVATORY OF CARLETON COLLEGE (Northfield, Minn.)

Founded: 1886, by Carleton College.

First Director: William Wallace Payne.

Present Director: E. A. Fath.

Major Telescopic Equipment:

16¼-inch equatorial refractor (Brashear).
8¼-inch visual refractor with correcting lens for photography (Clark).
5-inch meridian circle (Repsold).
6-inch photographic camera.

Universal spectroscope (Brashear).
Photoelectric photometer.

Principal Work: Study of variable stars by photo-electric methods; publication of *Popular Astronomy;* training of students in astronomical observation.
Financed by: Carleton College.
Staff: Two members.
E. A. Fath, determination of star magnitudes.
C. H. Gingrich, editor of *Popular Astronomy.*

HARVARD OBSERVATORY
(Cambridge and Oak Ridge, Mass.)

Founded: 1839, by the Corporation of Harvard University.
First Director: William Cranch Bond
Present Director: Harlow Shapley
Major Telescopic Equipment:
61-inch reflector (Fecker)
24-30-inch Schmidt camera
24-inch reflector
16-inch photographic refractor
12-inch photographic refractor
15-inch visual refractor (Merz & Mahler, Munich)
Harvard Observatory is now operating twenty-seven telescopes: fifteen at Oak Ridge and Cambridge, two at its solar observatory at Climax, Colorado, ten at Bloemfontein, South Africa (separately listed).

Principal Work: Celestial photography, astrophysical investigations; stellar and nebular photometry, stellar statistics; variable stars; meteor research and studies of the Metagalaxy.
Financed by: Harvard College and by special endowments and gifts.
Staff: Forty-nine members; outstanding members include:
Dr. Harlow Shapley, studies of the Metagalaxy.
Dr. Donald Menzel, spectroscopy and astrophysics.
Dr. Bart J. Bok, stellar statistics and interstellar absorption.
Fred L. Whipple, meteors, astrophysics, solar system astronomy.
James G. Baker, astronomical optics, astrophysics.
Walter O. Roberts, Supt. Climax Station.

Cecilia Payne Gaposchkin, stellar photometry and spectroscopy.

The observatory also has a station in South Africa, separately described.

LEANDER McCORMICK OBSERVATORY OF THE UNIVERSITY OF VIRGINIA (Charlottesville, Va.)

Founded: 1883, by Leander J. McCormick.
First Director: Ormond Stone.
Present Director: Harold L. Alden.
Major Telescopic Equipment:
26-inch visual refractor (Clark).
10-inch photographic camera with objective prism (Cooke).
6-inch visual refractor (Clark).

Principal Work: Determination of stellar parallaxes by photography; proper motions and spectra of faint stars.
Financed by: University of Virginia and grants from the family of Leander J. McCormick.
Staff: Five astronomers and two computers. Outstanding members include:
S. A. Mitchell, professor of astronomy and director emeritus.
Harold L. Alden, professor and director.
A. N. Vyssotsky, associate professor.
D. Reuyl, assistant professor.
E. T. R. Williams, instructor.

LICK OBSERVATORY OF THE UNIVERSITY OF CALIFORNIA (Mt. Hamilton, Calif.)

Founded: 1875, by James Lick.
First Director: Edward S. Holden.
Present Director: Charles Donald Shane.
Major Telescopic Equipment:
36-inch visual equatorial refractor with correcting lens for photography (Clark and Warner & Swasey).
12-inch equatorial refractor (Clark).
6½-inch meridian circle (Clark and Repsold).
36½-inch reflector (Grubb and Common).
20-inch double photographic refractor.

Principal Work: Radial velocities and proper motions of stars; double stars, both visual and spectroscopic; photography of

nebulæ, star clusters; studies of planets, satellites and comets.
Financed by: University of California, endowment and gifts.
Staff: Eight astronomers, four assistants, two fellows, one research associate. Astronomers include:

C. O. Shane	G. F. Paddock
J. H. Moore	N. U. Mayall
H. M. Jeffers	H. F. Weaver
F. J. Neubauer	G. E. Kron

LOWELL OBSERVATORY (Flagstaff, Ariz.)

Founded: 1894, by Percival Lowell.
First Director: Percival Lowell.
Present Director: V. M. Slipher.
Major Telescopic Equipment:
24-inch equatorial refractor (Clark).
42-inch reflector (Clark).
25-inch Schmidt (under construction).
13-inch photographic refractor, built especially for trans-Neptunian planet research.
15-inch Petitdidier reflector, used mainly at mountain station 11,500 feet above sea-level.
Principal Work: Study of the planets as planets, and of the origin, evolution and extent of the solar system; also, motions and nature of nebulæ, comets, etc.
Financed by: Trust fund of the estate of Percival Lowell.
Staff: Seven members, including.
V. M. Slipher, rotations and atmospheres of the planets, velocity study of spiral nebulæ and star clusters, and study of illumination of night sky.
C. O. Lampland, temperatures of the planets and photography of nebulæ.
E. C. Slipher, visual and photographic observations of planets.
Henry L. Giclas, staff assistant, studies of comets.
Stanley Sykes, instrument-maker.

McDONALD OBSERVATORY OF THE UNIVERSITY OF TEXAS (Mt. Locke, Texas)

Founded: 1932 by the University of Texas through bequest of W. J. McDonald, of Paris, Texas.

First Director: Dr. Otto Struve (also director of Yerkes Observatory).
Present Director: Same.
Major Telescopic Equipment:
82-inch reflecting telescope.
Principal Work: Stellar spectra, stellar photometry, research on nebulæ.
Financed by: University of Texas and University of Chicago.
Staff: Four members: W. A Hiltner, assistant director; Gerald P. Kuiper; Jesse L. Greenstein; Daniel M. Popper.

McMATH-HULBERT OBSERVATORY
(Lake Angelus, Pontiac, Mich.)

Founded: 1926 by Francis C. McMath, Judge Henry S. Hulbert, and Robert R. McMath.
First Director: Robert R. McMath
Present Director: Same
Major Telescopic Equipment:
Seventy-foot tower telescope with 12-inch by 50-foot focusing lens, also enlarging lens giving equivalent focal length of 100 feet; employed with 25-foot plane grating spectrograph, scanning and monochromatic energy-recording mechanisms, interferometer, and direct-photography camera.
Fifty-foot tower telescope, with 16-inch by 40-foot, and 12-inch by 20-foot focusing mirrors, and spectroheliograph. Also radial-velocity spectroheliograph with 10-inch by 25-foot focusing lens.
24-inch reflecting telescope, employing equivalent focal lengths of 50 and 100 feet, with motion-picture camera for lunar and planetary studies.
Principal Work: Solar physics, study of space motions and radiant energy of solar prominences and disc phenomena. Motion pictures of lunar and planetary phenomena.
Financed by: McGregor Fund of Detroit, University of Michigan and individual Detroit supporters.
Staff: Robert R. McMath
Orren C. Mohler
Leo Goldberg
John T. Brodie

MICHIGAN UNIVERSITY OBSERVATORY
(Ann Arbor, Mich.)

Founded: 1855, by University of Michigan.
First Director: Franz F. E. Brünnow.
Present Director: (Since death of Heber D. Curtis in 1942 no director has been appointed.)
Major Telescopic Equipment:
37½-inch reflector.
12-inch refractor.
15-inch reflector.
10-inch refractor.
97-inch reflector (under construction—time of completion not announced).
Principal Work: Spectrographic research, peculiar stars, variable stars, photography of celestial objects by the motion picture method.
Financed by: University of Michigan.
Staff: Seven persons, including:
A. D. Maxwell, acting chairman, Department of Astronomy.
D. B. McLaughlin, stellar spectra.
Hazel M. Losh

(The above data apply to Michigan Observatory and the student's observatory. The McMath-Hulbert Observatory at Lake Angelus, Mich. (see above), and the Lamont-Hussey Observatory at Bloemfontein, South Africa, are separately described.)

MT. PALOMAR OBSERVATORY OF THE CALIFORNIA INSTITUTE OF TECHNOLOGY
(Pasadena, Calif.)

Founded: 1928 by grant of funds from the General Education Board to the California Institute of Technology to construct the 200-inch telescope and an observatory.
Major Telescopic Equipment:
200-inch reflector (to be finished about 1947)
48-72 inch Schmidt camera
18-26 inch Schmidt camera

Principal Work: By agreement between the California Institute of Technology and the Carnegie Institution of Washington, the Mt. Palomar and Mt. Wilson observatories are engaged in a unit scientific program, under a single administrative management. For the principal work, see Mt. Wilson Observatory.
Financed by: The California Institute of Technology.

MT. WILSON OBSERVATORY OF THE CARNEGIE INSTITUTION OF WASHINGTON (Mt. Wilson, Calif.)

Founded: 1904, by George E. Hale under grant from the Carnegie Institution of Washington.
Past Directors: George E. Hale, 1904-1923; Walter S. Adams, 1923-1946.
Present Director: Ira S. Bowen
Major Telescopic Equipment:
100-inch reflector (figured by George W. Ritchey).
60-inch reflector (Ritchey).
20-inch reflector.
10-inch refractor.
6-inch refractor.
50-foot interferometer.
150-foot tower telescope.
60-foot tower telescope.
60-foot horizontal telescope.
Principal Work: The work of this observatory covers the entire field of astronomy, with especial emphasis on stellar and nebular photography and research, astrophysics, solar observation, stellar and solar spectrography, spectroheliography, planetary investigation, diameters of stars with the interferometer, etc.
Financed by: Carnegie Institution of Washington.
Staff: Twenty-one research workers, four research associates, and twelve computers. Research workers include:
Ira S. Bowen, director, nebular spectroscopy.
Seth B. Nicholson, solar physics.
Edison Pettit, solar physics.
Robert S. Richardson, solar physics.
Theodore Dunham, Jr., stellar spectroscopy.
Milton L. Humason, stellar spectroscopy, nebular photography.

Alfred H. Joy, secretary, stellar spectroscopy.
Paul W. Merrill, stellar spectroscopy.
R. F. Sanford, stellar spectroscopy.
Walter Baade, stellar photometry and nebular photography and spectroscopy.
Edwin Hubble, nebular photography and spectroscopy.
Adriaan van Maanen, trigonometric parallaxes and proper motion.
Harold D. Babcock, solar physics.
Edison Hoge, solar physics and photography.
Rudolf Minkowski, stellar spectroscopy.
Olin C. Wilson, stellar spectroscopy.
Ralph E. Wilson, stellar motions.
Arthur S. King, physical laboratory.
J. A. Anderson, physical laboratory.
Robert B. King, physical laboratory.

Research associates include:

Sir James Jeans, British cosmogonist and mathematician.
Henry Norris Russell, director, Princeton Observatory.
Joel Stebbins, director of Washburn Observatory, University of Wisconsin.
F. H. Seares, Mt. Wilson Observatory.

PERKINS OBSERVATORY OF OHIO WESLEYAN UNIVERSITY AND OHIO STATE UNIVERSITY
(Delaware, Ohio)

Founded: 1922, by Hiram Mills Perkins, professor of astronomy at Ohio Wesleyan University.
First Director: C. C. Crump.
Present Director: N. T. Bobrovnikoff.
Major Telescopic Equipment:
69-inch reflector.
6-inch photographic doublet.
9½-inch visual refractor.
4-inch transit.
Principal Work: Stellar spectroscopy.
Staff: Chief member is Dr. Bobrovnikoff, physical theory of comets.

PRINCETON UNIVERSITY OBSERVATORY
(Princeton, N. J.)

Founded: 1866, by the College of New Jersey, now Princeton University.
First Director: Stephen Alexander.
Present Director: Henry Norris Russell.
Major Telescopic Equipment:
23-inch visual refractor.
9½-inch equatorial refractor with accessories.
5-inch camera by Brashear.
Principal Work: Observations of eclipsing variables; theoretical work in astrophysics and spectroscopy.
Financed by: Princeton University.
Staff: Three professors:
Henry Norris Russell, astrophysics and spectroscopy.
J. Q. Stewart, physical researches.
S. Russeland, astrophysics.

STEWARD OBSERVATORY OF THE UNIVERSITY OF ARIZONA (Tucson, Ariz.)

Founded: 1916 through the gift of Mrs. Lavinia Steward.
First Director: A. E. Douglass (now director emeritus).
Present Director: E. F. Carpenter.
Major Telescopic Equipment:
36-inch reflector.
5-inch photographic refractor.
4-inch visual refractor.
Principal Work: Photography of Mars; photography and photometry of extra-galactic nebulæ; photographic and photoelectric stellar photometry; spectroscopy. A long and extensive investigation of climatic history, carried out by studies of the annual growth-rings of trees, was in December, 1937, transferred by the University to its especially established Laboratory of Tree-Ring Research, under the directorship of A. E. Douglass.
Financed by: University of Arizona and gifts.

Staff: Three astronomers, one fellow, student assistants. The astronomers are:

E. F. Carpenter, photometry, photography of nebulæ.
F. E. Roach, photoelectric photometry.
Paul D. Jose, assistant director; stellar photometry.

UNITED STATES NAVAL OBSERVATORY (Washington, D. C.)

Founded: 1830, as a Depot of Charts and Instruments, by the Secretary of the Navy and continued by action of Congress, 1842.
First Superintendent: Lieut. L. M. Goldsborough, U. S. N.
Present Superintendent: Commodore J. F. Hellweg, U. S. N. (Ret.).
Major Telescopic Equipment:

40-inch Ritchey-Chrétien reflector.
26-inch visual refractor.
15-inch Cooke-type wide angle photographic refractor.
12-inch visual refractor.
9-inch transit circle.
6-inch transit circle.
5-inch altazimuth.
8-inch photographic reflex zenith tube.
Twin 10-inch Cooke-type wide angle photographic refractors.
5-inch photoheliograph.

Principal work: National standard time service; America Ephemeris and Nautical Almanac; American Air Almanac; nautical instrument service for the Navy; visual and photographic observations of the sun, moon, planets, stars, etc., especially for position; fundamental positional astronomy.
Financed by: Federal appropriations.
Scientific Staff: Thirty-eight members, including:

G. M. Clemence, director *Nautical Almanac.*
Paul Herget, assistant director, *Nautical Almanac.*
Harry E. Burton, in charge of equatorials.
C. B. Watts, in charge 6-inch transit circle.
Paul Sollenberger, in charge time service and photographic zenith tube.
F. P. Scott, in charge of 9-inch transit circle.

WARNER AND SWASEY OBSERVATORY OF THE CASE SCHOOL OF APPLIED SCIENCE (Cleveland, Ohio)

Founded: 1919.
First Director: Dr. D. T. Wilson
Present Director: Dr. J. J. Nassau
Major Telescopic Equipment:

24-36-inch Schmidt-type telescope

Principal Work: Galactic studies
Staff: Dr. J. J. Nassau, Director

Dr. S. W. McCuskey—Professor of Mathematics and Astronomy
Dr. C. K. Seyfert—Assistant Professor of Astronomy
Miss Virginia Burger, Research Assistant
Mrs. Dorothy Gregg, Research Assistant

Financed by: Case School of Applied Science.

WASHBURN OBSERVATORY OF THE UNIVERSITY OF WISCONSIN (Madison, Wis.)

Founded: 1878, by Cadwallader C. Washburn, governor of Wisconsin.
First Director: James C. Watson
Present Director: Joel Stebbins.
Major Telescopic Equipment:

15-inch refractor (Clark).
6-inch refractor (Clark).

Principal Work: Photometry of stars with photoelectric amplifier, absorption of light in space, color of stars and nebulæ (investigations carried on in part at Mt. Wilson Observatory).
Financed by: University of Wisconsin.
Staff: Three astronomers, a research assistant and several student assistants. Members include:

Joel Stebbins.
C. M. Huffer.
Albert E. Whitford.

YALE UNIVERSITY OBSERVATORY (New Haven, Conn.)

Founded: 1830, by Sheldon Clark.
First Director: Denison Olmsted.

Present Director: Dirk Brouwer.
Major Telescopic Equipment:
Cœlostat: 15-inch photographic and 10-inch visual refractors of 50-foot focal length.
9-inch equatorial visual refractor.
8½-inch equatorial visual refractor.
5-inch wide-field camera.
Principal Work: Determination of stellar parallaxes and proper motions; minor planets, both theoretical and observational; occultations of stars by the moon; zone observations north of +10 degree declination; theoretical astrophysics.
Financed by: Yale University and endowment.
Staff: Sixteen persons, including:
Dirk Brouwer.
L. Spitzer, Jr.
V. Goedicke.
G. Laud.
I. Barney

YERKES OBSERVATORY OF THE UNIVERSITY OF CHICAGO (Williams Bay, Wisconsin)

Founded: 1897 by the University of Chicago from a gift by Charles T. Yerkes.
First Director: George Ellery Hale.
Present Director: Otto Struve.
Major Telescopic Equipment:
40-inch refractor.
24-inch reflector (Ritchey).
10-inch and 6-inch Bruce photographic telescope.
12-inch visual refractor.
6-inch ultra-violet photographic telescope.
Principal Work: Determination of stellar distances, measurement of double stars; star spectra; studies of the sun; determination of brightness and colors of stars; studies of nebulæ, comets and the Milky Way; stellar structure.
Financed by: The University of Chicago.
Staff: Fifteen scientific workers and ten technical employees. Important members include:
Otto Struve, astrophysics.

W. A. Hiltner, assistant director.
G. P. Kuiper, practical astronomy.
S. Chandrasekhar, theoretical astronomy.
W. W. Morgan, astrophysics.
Gerhard Herzberg, spectroscopy.
W. Albert Hiltner, astrophysics.
Louis G. Henyey, astrophysics.
Jesse L. Greenstein, astrophysics.
D. M. Popper, astrophysics.
W. S. Krogdahl, astrophysics.
W. P. Bidelman, astrophysics.

Observatories in the Southern Hemisphere

ARGENTINE NATIONAL OBSERVATORY (*Observatorio Astronómico de la Nación Argentina,* Córdoba, Argentina)

Founded: 1870, by the Federal Government of the Argentine Republic.
First Director: Benjamin Apthorp Gould.
Present Director: Enrique Gaviola
Major Telescopic Equipment:
60-inch reflecting telescope.
30-inch reflector
24-36-inch Schmidt telescope.
13-inch astrographic refractor (Henry Bros. and Gautier).
12-inch refractor (Clark).
7½-inch photographic refractor.
5-inch photographic refractor (Brashear).
5-inch refractor (Clark).
7½-inch and 5-inch meridian circles (Repsold).
Principal Work: Star catalogs, radial velocities of stars and nebulae; analysis of spectra; variables of the Magellanic Clouds; instrument design.
Financed by: The Argentine government.
Staff: Four astronomers besides the director; two physicists, eleven assistants. Includes:
Enrique Gaviola, spectra, instrument design.
Jorge Bobone, meridian circle, comets, asteroids.

Guido Beck, theoretical physics.
R. Platzeck, radial velocities, optics.
M. Dartayet, variable stars.

HARVARD OBSERVATORY, SOUTHERN STATION
(Harvard Kopje, near Bloemfontein, South Africa)

Founded: 1891 at Arequipa, Peru, moved in 1927 to South Africa; station originally established with funds bequeathed by Uriah A. Boyden.
First Superintendent: W. H. Pickering.
Present Superintendent: J. S. Paraskevopoulos.
Major Telescopic Equipment:
60-inch reflecting telescope.
60-60-inch Schmidt camera (unfinished).
24-inch refractor.
13-inch refractor.
10-inch refractor.
8-inch refractor.
Principal Work: Photography of the southern sky.
Financed by: Harvard University, endowment and gifts.
Staff: Six astronomers and assistants.

LAMONT-HUSSEY OBSERVATORY
(Naval Hill, Bloemfontein, South Africa)

Founded: 1927, by R. P. Lamont and Prof. W. J. Hussey.
First Astronomer in charge: R. A. Rossiter.
Present Astronomer in charge: Same.
Major Telescopic Equipment:
27-inch visual refractor.
Principal Work: Measurement and discovery of double stars in southern sky; nearly 7100 hitherto unknown double stars have been found.
Financed by: University of Michigan and the Municipality of Bloemfontein.
Staff: R. A. Rossiter, astronomer in charge.

ROYAL OBSERVATORY
(Cape Town, South Africa)

Founded: 1820, by the British Admiralty to promote practical astronomy and navigation by observing southern skies.
First Director: Rev. Fearon Fallows.
Present Director: J. Jackson.
Major Telescopic Equipment:
24-inch photographic refractor.
18-inch visual refractor.
13-inch astrographic refractor.
8-inch transit circle.
6-inch transit circle.
6-inch wide-angle triplet lens.
Photoheliograph.
Two 5-inch f/7 photometric lenses.
Principal Work: Accurate determination of the positions of stars by visual and photographic methods; photographic determination of stellar parallaxes; daily photographs of the sun; determination of time and emission of time signals; photographic and photovisual photometry.
Financed by: British Admiralty.
Staff: Fourteen astronomers, eight computers.

UNION OBSERVATORY OF SOUTH AFRICA
(Johannesburg, South Africa)

Founded: 1903, by the Government of the Transvaal (then a British colony), for meteorological service.
First Director: R. T. A. Innes.
Present Director: W. H. van den Bos
Major Telescopic Equipment:
26½-inch refractor.
Two 10-inch Franklin Adams star cameras.
Principal Work: Measurements of double stars; observations of minor planets; observation of lunar occultations.
Financed by: The Government of the Union of South Africa.
Staff: Seven members.

YALE UNIVERSITY OBSERVATORY, SOUTHERN STATION (Johannesburg, South Africa)

Founded: 1925, by Yale University.
First Director: Frank Schlesinger.
Present Director: Dirk Brouwer; Cyril Jackson, observer in charge.
Major Telescopic Equipment:
26-inch photographic refractor.
10-inch visual refractor (same mounting as the 26-inch).
5-inch wide-field camera.
Principal Work: Stellar parallax; proper motions of stars; positions of the moon, minor planets and satellites; zone observations from south of +10 degrees declination; parallaxes of nearly 1,700 stars have been obtained up to 1945.
Financed by: Yale Observatory.
Staff: Cyril Jackson.

INDEX

THE COMING AGE OF
ROCKET POWER

BY G. EDWARD PENDRAY

In an age when rocket warfare made headline news and jet propulsion is thought of as a comparatively new technique it is surprising to discover that it is in reality an age-old science. In *The Coming Age of Rocket Power*, the author, an authority in the field, traces the evolution of the rocket principle from its discovery in China centuries ago to modern wartime developments in the robot bomb, the bazooka and the jet propelled plane.

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Price $3.50

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The Author

G. Edward Pendray uniquely combines in one person the talents of expert publicist, writer and speaker, a public relations counsel to large corporations and an authority on science and engineering.

He is one of the country's foremost authorities on rockets and jet propulsion, and is interested in astronomy, telescopes, physics, electricity, meteorology and engineering. He has engaged in research in several of those fields.

Among the outstanding scientific and public relations projects with which he has been connected are the famous Time Capsule at the New York World's Fair, the national Annual Science Talent Search for unusually gifted boys and girls and the George Westinghouse Science Writer's Award.

He has written numerous articles in national magazines, several book-length magazine serials and one novel. His well-known book on rockets and jet propulsion, *The Coming Age of Rocket Power*, has attracted wide and favorable attention.

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PENDRAY

MEN, MIRRORS, AND STARS

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